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AN URBAN TRAFFIC SIMULATOR

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled AN URBAN TRAFFIC SIMULATOR submitted by Conrad G. Ferris in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

This thesis presents an urban traffic simulator in the form of a general purpose intersection simulation model. This general purpose model is designed to be used as a tool in the optimization of signal phasing schemes for single signalized intersections and networks thereof. Since the simulator is capable of handling both platoon and random arrival distributions, network optimization is possible on an intersection by intersection basis. Here platooned output from one intersection becomes platoon arrivals to the next and the bottlenecking influence of neighboring intersections is realistically accounted for in this way. Because the model is to be treated as a tool, it has been designed so that no previous computer or simulation experience is necessary for its effective use. The model is written in General Purpose Simulation System/360 and occupies 110K bytes of core. It is shown to be extremely flexible and its performance is rated as excellent in terms of realism and efficiency.

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CHAPTER I

THESIS INTRODUCTION

1.1 Introduction

In the past few years traffic conditions have come to present not only a technological but a sociological challenge. Lately there has been a general rise in the standards of living in every country of the world and this has been naturally accompanied by changes in ecology. Such changes have been exceptionally prominent in America. The technological revolution, while pouring millions of automobiles on the market, has urbanized the majority of the populace and has at the same time provided everyone with a previously unequalled affluence and amount of leisure time. Two results are obvious. The automobile is no longer the prerogative of the privileged few and the present day population is more mobile than it has ever been. But the era of the private car has brought not only benefits but problems of various kinds - for instance traffic jams, parking difficulties and increased accident rates. These problems are most intense in urban and suburban areas but nevertheless in existence from coast to coast. The current road system is inadequate to cope with the demands being made upon it and the result is to be found, not only in terms of death tolls and accident costs but also in terms of time, energy and money losses due, for example, to

delays from congestion.

Despite macabre highway statistics and the discomforts and costs of congestion, the motorist carries on. It would seem unlikely then that this new found and apparently highly valued personal freedom will be relinquished - at least in the near future. Although public transit is gaining popularity, most drivers still view transit as a solution to the extent that other drivers, not they, will leave their cars in their garages.[1] Even upon the complete acceptance of the transit system, personal mobility will not be entirely relinquished. The question arises therefore of how to organize and control road traffic so this increased mobility can be enjoyed to the fullest.

To answer the above question is, in essence, the job of the traffic engineer. Considering such objectives as the minimization of delay or travel time, a decrease in the number of stops, an increase in the smoothness of driving, and an increase in safety, he must fit traffic to the existing road system by regulation and control or he must fit the road system to the traffic by planning and redesigning.

1.2 The Problem

Problems of the road are complex. They involve laws

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[1]Donald R. Drew, Traffic Flow Theory and Control (McGraw-Hill Series in Transportation; New York: McGraw-Hill, 1968), 4.

of human nature on the one hand and physical laws of time, space and motion on the other. They are also many sided: they involve legal, constructional, educational and administrative factors. Furthermore problems of the road are evolutionary and exist in many levels of design, construction and utilization. There is no common technique with which all of the problems of the road can be approached. Moreover there are several problems which require a variety of approaches in their solution. To attempt to consider such a range of problems coincidentally would be foolish as well as substantially irrelevant. The concern here is with urban traffic and since the flow of traffic on city streets is generally limited by the capacity of intersections, intersections will be the target of scrutiny.

In designing a facility to handle the movements between two intersecting high-volume roadways, the designer must, on the basis of traffic demand, decide on the number of approach lanes needed and then apportion the time of the signal system. In most cases, whether it be the reconstruction of an existing intersection or planning a new freeway through the city, there are few alternatives considering the number of approach lanes. Therefore the problem becomes primarily one of signal time apportionment for an assumed intersection configuration.

1.3 Approaches to the Problem

There are several methods available for apportioning green time to the various phases of a signal cycle. The relative precision of these selections is proportional to the degree of realism achieved in the hypothesis regarding the arrival and departure rates. The simplest procedure is based on the assumption that the arrival rate is constant throughout the design hour and that the departure headways are constant throughout the green interval. Thus, the ratio of the duration of a given phase to the total cycle length is equal to the demand on the given phase divided by the demand on all phases. This has been referred to as the G/C method, where G and C refer to the durations of the green phase and the cycle length respectively.

The above noted demand allotment method of phasing a signal system is completely lacking in terms of level of service. This is to say that no consideration is given to the measures of quality of driving which represent time, money and energy losses as well as safety factors to drivers and pedestrians. These measures can be generally viewed in terms of travel time, time in queue, number of stops or delay time. Delay time can be defined as the actual time taken to pass through the intersection above and beyond the time taken to pass through the intersection with no vehicle or signal obstructions. Since the level of service is of particular importance to the driver, it must be included in

signal phasing considerations.

A variety of stochastic models and fluid analogy models have been derived which account for the level of service of signal controls.[2,3,4] These models are generally based on uniform or Poisson arrival rates and as such are not completely realistic. Drew[5] shows that either assumption has limitations. For the peak period (the critical service time) the assumption of uniform arrivals is less reliable. In any case all such models suffer further from apriori simplifying assumptions. For example, both queuing theory and the fluid analogy approach neglect driver-vehicle factors and cannot account for vehicular or vehicle-system interaction. In particular vehicles cannot respond to changing conditions. Furthermore the continuous flow approach represents the limiting behavior of a stochastic process for a large population and is applicable to large scale problems only. In conclusion, the mathematical and physical models in existence are somewhat rigid. They all suffer from extreme complexity in all but the most trivial situations. Such complexity usually tends to obscure, rather than

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[2]G.F. Newell, "Queues for a Fixed-Cycle Traffic Light," Ann. Math. Statist. 31, No. 3, 589-97 (Sept. 1960).

[3]A.J.H. Clayton, "Road Traffic Calculations", Journal of Instruction for Civil Engineers, 16, 247-284.

[4]F.V. Webster, "Traffic Signal Settings", Technical Paper 39, Road Research Laboratory D.S.I.R. (1958).

[5]D.R. Drew, Traffic Flow Theory and Control (McGraw-Hill Series in Transportation; New York: McGraw-Hill, 1968), 290.

illuminate, the real system interaction and in this sense is inhibitive to insight.

At this point it would seem desirable for the engineer to have at his disposal an alternative approach - one with the power to employ the beneficial aspects of previous approaches and at the same time compensate for their deficiencies. This new method should be capable of accounting for the real inter-vehicle-system action in deterministic terms and for real driver-vehicle-system parameters in stochastic terms. The method should also be capable of utilizing accumulated real data. Furthermore this approach should be sufficiently flexible to be applied to numerous situations and be capable of producing performance measures in terms of the previously defined control objectives. The operation of such a powerful composite model would not only produce reliable results but would, in all probability, foster understanding of the real situation. Such an approach is offered in the name of simulation.

This thesis presents an intersection simulation program to be used, as a tool, by the traffic engineer in promoting increased efficiency of signal systems.

Chapter II is a brief review of some of the techniques in use in the simulation of traffic flow. A selected number of publications are reviewed in order to demonstrate the variety of simulation approaches.

Chapter III opens with a presentation of model

perspectives. Relevant considerations are discussed briefly and a description of the general purpose simulation model is presented. Flow charts depicting non-turning, left turning and right turning vehicle movements are included in Appendix C.

Chapter IV deals with model validation and further refinement. Here the model is validated by comparing real and simulated data and an evaluation is made as to the expendability of various simulator features in terms of computer time and model accuracy. This evaluation is based on simulator performance for a control intersection.

Chapter V contains a summary of the significant findings of Chapters III and IV and some propositions for future research.

CHAPTER II

SIMULATION AND TRAFFIC FLOW

2.1 Simulation Proper

The concept of simulation which shall be used throughout this paper is that used by Martin.[6] Simulation is the technique of programming a logical-mathematical representation of a concept, system, or operation for solution on a high speed computer. The purpose of simulation is to represent or "model" the actions and interactions of the elements of a system so that the effectiveness or level of service of the system can be determined for any set of conditions. A computer simulation model may contain all or some of the features of deterministic, stochastic, or expected value models.

In discussing simulation, it is convenient to classify models into two major types: continuous change models and discrete change models. These classifications are also referred to as macroscopic and microscopic respectively.

2.1.1 Macroscopic Models

Continuous change models are appropriate when the analyst considers the system he is studying as consisting of a continuous flow of information or material counted in

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[6]Francis F. Martin, <u>Computer Modelling and Simulation</u> (New York; John Wiley and Sons, Inc., 1968),5.

the aggregate rather than as individual items. These models are usually represented mathematically by differential or difference equations that describe rates of change of the variables with respect to time. As such, the simulation of these models is particularly suited to analog computers. They can however be implemented on digital machines by using finite difference equations as approximations to the differential equations of the continuous flow. In many cases the latter approach is used because of the accuracy and the versatility of the digital machine.

2.1.2 Microscopic Models

In microscopic models, changes in the state of the system are conceptualized as discrete rather than continuous and items are considered individually rather than in groups. Systems are idealized as network flow systems and are characterized by the following;

The system contains components or elements or sub-systems each of which performs definite and prescribed functions. For example a traffic system is composed of intersections, roadways, bridges etc. and subsystems thereof.

Items flow through the system from one component to another, requiring the performance of a function at each component before the item can move onto the next component. Take for example street traffic. A given vehicle must

traverse a section of roadway before encountering an intersection. The function or service of the intersection then becomes a prerequisite for the service of the next section of roadway or whatever. Vehicle motion can then be accounted for in terms of the services of the traffic system components.

Components have finite capacity to process the items and therefore, items have to wait in queues before reaching a particular component. The intersection is a striking example of a traffic system component with a finite capacity.

Discrete or microscopic models are directly associable with digital computers.

From time to time situations have arisen in which simulation features of both the analog and digital computers were desirable (for example a macroscopic model with a variety of system constraints). Often, in these cases, analog-digital converter equipment has been employed and the simulation has been appropriately termed hybrid.

The desired or necessary output from any simulation model is a summary of the state changes of the system with respect to time. This summary is usually presented as frequency tables, graphs, queue statistics, maximum values, etc.

2.1.3 Advantages of Simulation

A multitude of advantages have been cited for the technique of simulation. They include:

1. Decisions concerning future systems in a conceptual stage can be easily made.
2. System performance can be simulated and observed under all conceivable conditions.
3. Results of field system performance can be extrapolated on a computer simulation model for purposes of prediction. Given field performance data, the interpretation of the data can be expanded in a probabilistic context.
4. System trials can be speeded up by incredible orders of magnitude.
5. Artificial yet realistic data on a system can be provided quickly and in large quantities without having to exercise the real world system.
6. Chance elements associated with a system can be implemented to determine system outcomes in a probabilistic context. Chance element parameters can be controlled in order to study their effects on system performance. The user has complete control over the probabilistic parameters and can select any desired combination of parameters to exercise the model.
7. The task of laying out and operating a simulation

is a good way to systematically gather pertinent data.

8. Simulation may provide an indication of which variables are important and how they relate.
9. Simulation is cheaper than many forms of experimentation.
10. Simulation gives an intuitive feeling for the system being studied and is therefore instructive.

2.1.4 Disadvantages of Simulation

The disadvantages of simulation are relatively few but are of significant importance. They include:

1. Considerable effort is required in the programming of a simulation model of any complexity.
2. Simulation may become overly costly. Consideration must be given to man-machine feasibility.
3. Any model contains a danger of pseudo simulation. Given reasonable faith in the simulation process, an unvalidated or erroneously validated model may persuade decision makers to formulate policy which will have costly results.
4. Accurate and detailed data is essential to any model.

It should be noted however that these disadvantages also apply to most analytical models. Therefore let us now turn to the application of simulation in traffic flow.

2.2 Traffic Simulation

Considering the formerly stated overall goals of traffic organization and control and the above listed advantages of simulation, it is not surprising that the applications of simulation to traffic problems are extensive. Simulation has successfully been employed in the design, construction and utilization of traffic systems such as tunnels, freeways, bridges, traffic circles, bypasses, toll gates, intersections and networks of intersections. It has also contributed substantially to understanding in these areas.

> For the most part it can be said that the goals achievable by simulation in the traffic process are clear cut and offer a rewarding payoff. Simulation is an ideal technique for traffic research. The simulation model is not just another means of accomplishing what we can do today but it is a tool for solving problems which cannot be solved today.[7]

Once again however caution in the traffic model is urged. Traffic simulation has a distinct advantage in being safe but the unquestioning implementation of simulation results could well prove fatal. The following comment by Gerlough, regarding extensive testing of intersection phasing and control techniques upon simulation results, clearly indicates the danger.

> One interesting finding of the field tests vividly illustrated the appropriateness of

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[7] Donald R. Drew, Traffic Flow Theory and Control (McGraw-Hill Series in Transportation; New York: McGraw-Hill, 1968),286.

> conducting environmental studies to complement theory and simulation. In the simulation tests of new control concepts, green phases as short as ten seconds were utilized. In descriptions of the laboratory tests, the practice of many agencies using initial and vehicle intervals such that the first car may have fifteen seconds of green was mildly criticized. However in the initial field implementation tests, vehicle behavior was erratic when a ten second minimum green phase was attempted as part of the basic queue control mode. So glaring was the misbehavior that only a few minutes of testing were tolerated before the decision was made to switch back to local control. Subsequently a revised minimum green parameter of fifteen seconds was incorporated, and thereafter no driver behavior problems were encountered.
>
> This interpretation may seem to be a matter of hairsplitting, but apparently the problem was not the short green but the short red. Many drivers who were stopped first in line on the red evidently did not expect their wait to be over so quickly, and responded very sluggishly when the signal changed back to green. This behavior is attributed to the ever recurring long signal cycles on the streets the drivers traverse, but it should not be concluded that fifteen seconds minimum green is a natural constraint necessitated by driver limitations.[8]

Since the major considerations of any simulation model are the degree of realism incorporated and the actual computer run time of the model, the model should be designed to simulate only those aspects of the prototype which influence the problem under study. Characteristics which may be considered for inclusion in the traffic model are:

1. Drivers make decisions at variable time intervals, dictated by changes in the traffic situation.

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[8] D.L. Gerlough and F.A. Wagner, "Improved Criteria for Traffic Signals at Individual Intersections," National Cooperative Highway Research Program Report 32, (1967),22.

2. Drivers have a finite, non-zero reaction time.
3. Vehicles have finite acceleration and deceleration limits, and maximum speeds.
4. Vehicle speeds are governed by speed regulations, driver temperament etc. as well as by factors mentioned under (3).
5. Vehicles are characterized by their size, power and various mechanical properties.
6. Drivers (or pedestrians) have limited ability to judge headway distance and vehicle speeds.
7. Drivers (or pedestrians) are affected by psychological traits, fatigue, the weather and so on.
8. Traffic attributes:
   (a) speed distributions;
   (b) concentration distributions;
   (c) volume;
   (d) lateral distribution (number of lanes in each direction);
   (e) parked vehicles or obstructions.

Obviously the level of detail could become overwhelming but it has been shown that even crude models give surprisingly good results. The level of detail should be controlled by the purpose of the simulation, the power of the language for the simulation and/or the computer (funds) available. Such limiting conditions should be well defined prior to problem definition. In order to gain a little more insight

toward traffic simulation, let us look briefly at some of the models currently in existence.

2.3 Analog Intersection Simulation

The University of Manchester's Electrical Engineering Department has developed a special purpose computer hardware package for the simulation of intersections. This special purpose machine is called the road traffic simulator.

The road traffic simulator is not purely an analog machine but a hybrid. It has incorporated, in hardware, digital circuitry as well as analog facilities so it is capable of handling discrete numbers as well as continuously varying quantities. Programming includes simple patch cord interconnections of each of the basic subunits - each of which is fully controllable. A high degree of correspondence to real-life traffic situations is achieved by the use of simple logical rules to control the behavior of vehicles in the model.

Vehicles are generated on approach lanes by a random pulse generator according to a Poisson distribution. The mean of the Poisson distribution is controllable and the random pulse generator can be reset so that identical arrivals can be simulated. Each pulse from the generator is of the same strength and all vehicles are therefore homogeneous.

Queues are maintained, on the approach lanes, by the

innovated digital circuitry which is simply a group of binary counters. Maximum queue length is sixty-three. Queues are dispersed, when permitted, at a discharge rate which is a function of the vehicle concentration in the queue.

Roadway representations are included in subunits called streets which are connected between the respective random pulse generator and digital queue counter configuration. The time it takes a vehicle to travel a portion of the road is accurately represented. Streets are also interconnectable and side street entries are possible. The presence or absence of a pulse (vehicle) along a main street is input to the side street controller and this feedback is used to realistically simulate gap acceptance or rejection by entering vehicles. The same type of feedback approach is used for conflicting turns.

The traffic signal controller is somewhat rigid in that it only provides for a two-way phasing scheme. Green times for each direction are alterable but the amber is constant for all phases.

System output is simply a summary of queue lengths on paper tape. This paper tape is then input to a digital machine, with a conversion package, and summary statistics on length of queues are provided in printed form.

Although the system configuration is not very flexible, it has shown favorable results in a variety

of standard situations. The hybrid in this case has two distinct advantages over the digital machine - (1) it can be used for traffic simulation twenty-four hours a day and (2) it is fast. Ratios of fifty to one, real time to computer time can be implemented.

Although the equipment is relatively inflexible and, at least initially, costly, Hartley and Green feel that the simulator or its prototype will be the least expensive method of simulating the standard two-way intersection.[9]

2.4 Digital Simulation

In the last few years digital machines, because of increasing size, speed and versatility, have become increasingly popular for simulation. As a result a variety of general purpose as well as special purpose simulation packages have emerged. Examples of such packages are I.B.M. General Purpose Systems Simulator (G.P.S.S./360) and SIMSCRIPT. The purpose of these and other such packages is to relieve the analyst of severe clerical duties and allow him to represent a model in more familiar notation. Even with the existence of such packages, standard programming languages are still widely used.

Every digital simulation, whether by standard

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[9] M.G. Hartley and D.H. Green, "Study of Intersection Problems by Simulation on a Special Purpose Computer", <u>Traffic Engineering and Control</u>, July (1965), 219.

language or by simulation package, has a least one common book-keeping task - that of updating the simulator clock. Since state changes of the system occur in discrete time intervals, some method of synchronizing state changes and real time changes is required. A reasonable solution is to synthesize a real time clock and to evaluate state changes in terms of this synthetic clock. When all the state changes for the current time have been accounted for, the clock must be updated and the now pending state changes accounted for. Simulation packages maintain this clock and correlate events automatically. With a standard programming language the user must account for clock and state changes. Whether the system accounts for the timing or whether the programmer accounts for the timing, two methods of clock update are available. These are referred to as the periodic scan and the event scan.

In the periodic scan method, one divides the duration of the simulated phenomenon into a number of successive time intervals displaced by time periods. In the event scan method, after a given event has occurred, one determines and stores a set of imminent significant events and times at which they will occur, and selects the earliest. In essence, the periodic scan method asks what the situation will be one time unit from now, whereas the event scan method asks at what time unit is the next most imminent event to occur. Generally speaking, event scanning saves

execution time but requires more programming and more computer storage.

Assuming that the clock feature of the digital simulation has been accounted for, the analyst might consider the type of vehicle-roadway representation to be used. For single intersections the microscopic approach is usually employed. When considering intersection networks the large amount of real traffic may make the macroscopic approach imperative because of computer time and core storage requirements. Again the choice will be a function of the available facilities and the desired level of detail in the model. It would be advantageous at this time to more closely examine some possible vehicle-roadway configurations.

2.4.1 Micro-Representations

In the micro approach vehicles are to be accounted for as individual entities. This implies that provision must be made for "remembering" each vehicle's position. This is usually done in one of three ways: (1) Physical representation, (2) Intersection cell representation, and (3) Memorandum representation.

Physical representation - Before proceeding it should be noted that the implementation of this method requires considerable familiarity with computer hardware configurations. Here actual physical computer core locations, preferably contiguous, constitute a lane of the roadway.

A vehicle is represented by a one or a configuration of ones in the core locations composing the road. Since everything is in binary, it is convenient to allow zeros to represent spaces. Then different configurations of ones represent different vehicles. For example if 11 represents a car, then 111 might represent a bus and 1 possibly a motorcycle. Since the locations of computer core areas are normally referred to as words (or bytes), the roadway can be considered to be broken down into cells. The vehicle capacity of each cell will depend upon the core configuration of the computer being used. In any case vehicle motion is accomplished by moving the vehicle representations through the contiguous core areas at a rate commensurate with that at which the real vehicles traverse the roadway. The mechanics of this motion is provided by binary multiplication. The core representation of the roadway must therefore have vehicles progressing toward lower core areas.

Consider the following example. Assume that the cell length is one byte or eight bits. Assume also that the hardware configuration of the computer being used limits arithmetic operands to eight bits. Assume also the vehicles are represented on a roadway by the following cell configuration.

Cell 1	Cell 2	Cell 3	Cell 4
00110001	11001110	00011010	11000011

Furthermore assume that 11 is a passenger car and that the flow in the lane is 22 feet per second. Since a passenger car requires about twenty-two feet to parallel park, in one second all bits must move two bits to the left. Therefore for 22 feet per second a multiplying factor of 2^2 is required. The byte multiplication is carried out in order of ascending core locations. By definition the leftmost location is the end of the roadway or intersection or whatever, so overflow from location 1 is forgotten. Overflow from subsequent byte multiplication however must be superimposed in the next byte as the least significant bits. After a one second update, the configuration of the above word is:

Cell 1	Cell 2	Cell 3	Cell 4
11000111	00111000	01101011	000011__

The least significant bits (shown as blanks) will be zeros if no vehicles have joined the line within the last second.

If the vehicles are moving at different velocities, they will be stored in similar channelled blocks of core and multiplied by different powers of two. At each update the velocity channels for each lane would then be merged and checked for conditions of overtaking. If a vehicle is found to have overtaken its leader a decision is then made to slow down or change lanes. Either is accomplished

by transferring the vehicle configuration to a different channel block.

Deceleration and acceleration as well as stopping can be successfully accounted for by a step-channel process whereby a vehicle slowing to a stop successively occupies channels with multipliers $2^n, 2^{n-1} \ldots 2^0$ where it is deemed to have stopped. The same process in reverse could successfully account for acceleration factors.

Although this method appears to be widely recognized as a possible approach to traffic simulation its use seems very limited.

Intersection cell representation - This method of representation appears to be a natural extrapolation from the physical model. Here the roadway and/or intersection is again broken down into cells but these are represented in language or software attributes rather than hardware. Such features as matrices in FORTRAN or storages and logic switches in G.P.S.S./360 are applicable. Differing also is the size and capacity of cells. Here words replace the bit configurations for indicating vehicle occupancy. Each cell in this case can be occupied by at most one vehicle, however a single vehicle may occupy more than one cell if it is in motion. Vehicle positions are again accounted for by the status of cell indicators. There are two methods of moving vehicles. The first method implies choosing cell length such that the average vehicle, if unrestricted, will cover

the cell in a unit time. The second method is that of choosing cell length and employing some deterministic formula in the setting and resetting of the cell indicators. For example: the time a vehicle of speed V occupies a cell of length L is L/V. The first of these methods appears, as does the physical representation, to be more suited to the periodic scan whereas the latter method is suited to the event update approach.

Blum[10] successfully applied G.P.S.S./360 to an intersection simulation using the second approach outlined. Only the junction itself was broken down into cells and vehicles travelled through these cells according to a time-distance function. Each of the cells were numbered and turners were routed according to cell number functions. Conflicting left turners waited, or were delayed, until a superimposed cell (storage), composed of all oncoming possibly conflicting lanes, was completely free of traffic. Vehicles were generated according to a Poisson distribution and were delayed only by blocked turners or red lights - the amber signal was not considered. Treatment within the intersection was exceptionally slight in order to keep computer time down and enable network simulation. This effect was achieved and a network of ten intersections was simulated with a run time to real time ratio of one to one.

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[10] A.M. Blum, "Digital Simulation of Urban Traffic," I.B.M. Systems Journal. Vol. 3, #1, (1964), 41.

No indication is given however as to the accuracy of the model or to the criteria for phasing evaluation other than the queue statistics maintained automatically by G.P.S.S./360.

Memorandum representation - Memorandum is commonly accepted to mean a short written note for future use. As such this method is aptly captioned. Representation here is by bits, bytes or words of computer memory uniquely associated with each vehicle. These defined memory locations are referred to as vehicle parameters and contain such things as current velocity, current acceleration, and current position. These parameters can also be used to denote driver attributes such as reaction time and target velocity. In order to maintain prevailing conditions, the status of each vehicle parameter that is subject to change is checked, and updated if necessary, at every potential change condition. In employing this status check either the periodic or event scan technique may be used. The memorandum method is the most widely used for individual intersection simulation at the micro level. In general when vehicles are not treated as homogeneous entities some form of this method becomes imperative. All general purpose simulator packages employ the memorandum technique. Once again such packages relieve the analyst or the engineer of the task of providing for and remembering parameter locations.

2.4.2 Micro-Simulation Examples

A Single Intersection

A most well defined and detailed microscopic simulation of an intersection was done by Gerlough and Wagner of the Planning and Research Corporation at Los Angeles.[11] Their simulation employed the memorandum method of vehicle parameters, the periodic scan and clock update technique and was implemented with a standard programming language - FORTRAN II. Following is a brief summary of their simulation model and their interesting results.

The simulation model is of a single signalized intersection but the model is general purpose so that it can be applied equally well to any intersection. The physical roadway represented is the orthogonal intersection of two six-lane, bi-directional roadways. Each artery corresponds to a unique coordinate system - the origin of each being at the intersection entry line and the positive scale in the direction of the flow.

Vehicles are generated at system entry points according to a headway distribution developed by Kell.[12] Each vehicle is identified with a lane-list which corresponds to its directional coordinate system,and turning

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[11] D.L. Gerlough and F.A. Wagner, "Improved Criteria for Traffic Signals at Individual Intersections," National Co-operative Highway Research Program Report 32, (1967),22.

[12] J.H. Kell, "Analyzing Vehicular Delay at Intersections Through Simulation, "Highways Research Board Bulletin 356, (1962), 28.

movements are accomplished by transferring vehicles from a particular lane list (originating) to another (turn completion lane list). Right turns are assumed congruent whereas left turns have two configurations - one for free flow turns and one for conflicting turns. Maximum turn velocity is derived according to the turn radii and is sustained throughout the turn in all free flowing cases. Pedestrian effects are considered negligible.

Each vehicle has associated with it eleven computer words containing such parameters as position, velocity, acceleration, actual length, effective length, target velocity, maximum desired acceleration, desired negative acceleration, system entry time, stopped position and a flag word containing vehicle identification, turn indicator, vehicle type, etc.

Vehicle motion is evaluated deterministically according to car following theory. Either a vehicle is a follower or a leader. A vehicle is a leader if it is first on a list or if its free flow motion is uninhibited by preceding vehicles - otherwise it is a follower. Vehicle acceleration is calculated every period (.25 seconds) according to the following formulae:

$$Acc(J,I+T) = K[TVEL(J,I) - Vel(J,I)]$$

where: $Acc(J,I+T)$ = acceleration of leader (vehicle J) at time I+T;

TVEL(J,I) = target velocity of vehicle J;

Vel(J,I) = current velocity of vehicle J;

K = proportionality coefficient - determined experimentally;

I = current simulator clock time;

T = reaction time - constant for all vehicles/drivers.

$$Acc(J+1,I+T) = Ao\frac{[Vel(J,I) - Vel(J+1,I)]}{Pos(J,I) - Pos(J+1,I)}$$

where: Acc(J+1,I+T) = acceleration of car J+1, the follower at time I+T

Vel(J,I) and Vel(J+1,I) = velocities of leader and follower at time I;

Pos(J,I) and Pos(J+1,I) = positions of leader and follower at time I;

Ao = characteristic speed of vehicles determined experimentally.

For a detailed evaluation of constants K and Ao see Appendix A.

In evaluating vehicle motion the most restrictive acceleration equation is employed. Updates consist merely of applying these equations of motion to each vehicle every period. There are however other considerations which are also checked every period. These include such things as

statistics as well as slowing and stopping behavior which is not handled as a special case of car following theory.

Slowing down and/or stopping occur in a variety of situations - red light approaches, amber light approaches and blocked turns. The driver philosophy utilized here is that a vehicle approaching any obstruction will not exhibit slowing behavior until the rate of deceleration required to slow down or to stop is greater than the driver desired rate of deceleration. Since this desired rate of deceleration is tagged on each vehicle this approach is easily implemented. Furthermore, once a vehicle attains such a deceleration a target stopped position is attributed to the vehicle and this rate of deceleration will be sustained until the vehicle stops or until the situation changes. Since a time lag is inherent in all reactions some error is liable in stopping at the desired stop position. In queue build up this error is realistic as different vehicle spacings do naturally occur in the real situation. However when a vehicle stops at the stop line, an error of this nature could mean that the stopped vehicle was partially in the intersection. In the simulation model this latter condition is checked for. If the first in line vehicle overshoots the stopline the vehicle is accelerated at maximum through the intersection. If the vehicle undershoots the stop line by a significant amount the vehicle is subjected to a small acceleration such that it resumes

motion and re-iterates the stopping procedure with a new target stopped position - the actual stop line. In all cases a small amount of error is tolerated.

Three stochastic properties are included in the model as driver decisions. These decisions are in response to the amber signal and in response to a gap or a lag in conflicting traffic (for initiating right turns, for completing left turns or for changing lanes). In essence the procedure for each decision is the same. At a decision point an evaluation is made of the time to possible conflict. This is done by actual list scanning evaluative procedures. This time is used as input to a probability of acceptance function which is derived from real data. A random number is now generated and compared with the probability of acceptance value and the decision finalized. Examples of the probability functions used are included in Appendix A.

Traffic measures included in the model are excellent. A novel feature of these measures is a vehicle detector routine which may be specified as being positioned anywhere in the coordinate system. Output from the detector routine is a complete analysis of vehicle flow at the specified position and is particularly valuable in model validation. Detector analysis includes such things as vehicle velocity, vehicle spacing, vehicle delay at a given position, etc. Queue statistics are also provided for on the basis that vehicles are deemed in queue when they become stopped behind

another vehicle which is in queue. If no preceeding vehicle exists, a vehicle enters a queue when required to stop at the stop line. Vehicles are not removed from their respective queues until their position is concurrent with the appropriate intersection discharge boundary. Further analytical statistics are allowed in the periodic scan. These include number of stops and stopped time per vehicle. In all cases means and measures of dispersion are provided.

The model is rated as excellent in terms of realism however no statistical measures of the goodness of fit of simulated to real data are offered. The model is completely detailed and flexible and it is also reasonably fast. The average computer time to simulated time ratio on an I.B.M. 7094 was about one to five.

Significant results to emerge from the above study, via simulation, include the following.

> An inescapable conclusion that emerged time and again during the project is the overriding influence of signal-cycle length on effectiveness of performance. Traffic engineers are urged to conduct thorough studies of individual intersections and systems and to strive for the reduction of cycle length wherever appropriate.
>
> A special study on the relative effectiveness of various phasing schemes incorporating protected left turns was successfully completed. ... The results dramatically illustrated the reduction in delay experienced whenever efficiently timed two-phase operation can be employed ... Surprisingly, the evidence indicates an increasingly significant advantage of two-phase

signalization as traffic volume rises.[13]

Further testing was done considering the minimization of delay for any intersection. The usual approach to this problem is to minimize the average delay to all users. However this approach was found liable to a large degree of imbalance in delay to users in different approach arteries. A theoretical analysis showed that the policy of equalization of delay among intersection arteries was a rational one virtually synonomous with delay minimization.

Some traffic engineers consider that reducing the number of vehicles required to stop is the most important feature of a signal control technique. In order to define some degree of relative importance between delay and stopping a theoretical analysis was invoked. Relevant costs were established for a vehicle mix of ten percent single unit trucks and ninety percent passenger vehicles with an approach speed of forty miles per hour as:

Vehicle cost per stop = 0.710¢;

Vehicle idling cost = 0.292¢ per minute;

Road-user time cost = 2.375¢ per minute.

If for a given period of time, one can determine total number of vehicles stopped, total stopped delay, and total

[13] D.L. Gerlough and F.A. Wagner, "Improved Criteria for Traffic Signals at Individual Intersections", National Co-operative Highway Research Program Report 32, (1967),2.

system delay, the total incremental travel cost for the period can be computed as follows:

$$dC = 0.710\ N + 0.292\ Dst + 2.375\ Dsys$$

in which:

dC = total incremental travel cost;

N = the number of vehicles stopped;

Dst = total stopped delay;

Dsys = total system delay.

For any given analysis, such an economic consideration would be the most objective way of determining true performance. With this in mind the following final results seem significant.

Mean system delay (a so called primary measure of effectiveness) was correlated to the so called secondary measures of performance (mean stopped delay, mean stopped delay per stopped vehicle, mean queue length, mean delay in queue, and proportion of vehicles stopped). The results showed that all five of the secondary measures were very strongly correlated with mean system delay. Validated regression equations for this analysis are included in Appendix A.

An Intersection Network

A microscopic simulation of an intersection network was done by a graduate student, Wulf D. Watjen, of the

Technical University of Denmark.[14] This simulation model represents three intersections and is implemented in a general purpose simulation language - G.P.S.S./360.

The aim of this study is to investigate the delay of vehicles traversing the three intersection network using a variety of synchronizing offsets. The model comprises only a single lane of one-way traffic and the signal scheme at each of the three intersections is fixed. The only variables in the model are the offset of signal two from signal one and the offset of signal three from signal two.

Vehicles are generated according to a Poisson distribution and are queued at the first signal. On release from the first signal (signal turns green) the queue is dispersed according to a headway distribution, which is normal, with a mean of two seconds and a mean deviation of .5 seconds. Vehicles are assumed to retain this distribution until the next signal which is reached after a constant delay of twenty seconds. The same process is repeated from the second to the third signal.

Validation for this system is supported by agreement of queue measures between the simulation model and Webster's analytical queueing model for the first light. No real statistical comparisons are made.

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[14] Wulf D. Watjen, "Computer Simulation of Traffic Behavior Through Three Signals", Traffic Engineering and Control, (Feb. 1965),623.

Results of the study show that offsets are optimal when they exactly equal the travel time between the two signals. They further show that if such offsets are not attainable, for some technical reason, it would be better to use offsets of less than the travel time rather than offsets of more than the travel time. Furthermore Watjen claims that the minimization of delay of the third signal is largely effected by the delay of the second signal and suggests that optimization in terms of delay time cannot be accomplished on an individual intersection basis.

The study seems to be oversimplified in many aspects. Firstly no consideration is given to any other traffic in the scheme which delay optimization techniques must account for. Secondly the study is concerned only with one volume level and no consideration is given to the possible performance fluctuations for both lighter and heavier traffic. Finally it seems that Watjen is not optimizing the offset from signal one to signal two when the influence from the first offset is considered as effecting the efficiency of the second. The study does show however that G.P.S.S./360 is handy for such small scale, non-detailed simulations and that inter-signal influences should be considered.

Let us now turn our attention to larger network models.

2.4.3 Macro-Representations

By treating vehicles in bunches, macroscopic models have the advantage of being able to represent networks of intersections efficiently in terms of computer time and space. They suffer, however, in terms of detailed realism for any individual intersection. Macro models are best explained by examples.

2.4.4 Macro-Simulation Examples

The majority of macroscopic traffic simulations have the same approach - divide the roadway into coarse segments and keep track of the number of vehicles in each segment. Variations of this approach are used by Sakai and Nagoa[15] and by Gerlough.[16] The length of roadway segments is dictated by current traffic conditions and the detail desired in the simulation. The length of the cells is usually equal to the mean distance an average vehicle will cover between updates. The method known as the periodic scan is therefore employed.

Sakai and Nagoa have employed a periodic scan of four seconds and a mean cell length of fifty meters in a

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[15]Toshiyuki Sakai, and Makoto Nagoa, "Simulation of Traffic Flow in a Network", Communications of the A.C.M. (Vol. 12, No. 6, June 1969),311.

[16]D.L. Gerlough, "Simulation as a Tool in Traffic Control System Evaluation", Traffic Control Theory and Instrumentation, (Thomas Hortin, I.B.M.; New York: Plenum Press: 1965),71.

model of a downtown section of Kyoto, Japan. Vehicles are transferred from block to block according to the following formula.

$$Dq_{ij} = \tfrac{1}{2}[V_i \cdot V(q_i/Q_i) + V_j \cdot V(q_j/Q_j)]DT\ q_i/l_i$$

Where: V_i = maximum speed allowed in block i;

q_i = number of vehicles in block i;

Q_i = maximum number of vehicles allowed in block i;

$V(q_i/Q_i)$ = mean speed of vehicles in block i; evaluated according to relative density function shown in Appendix B;

DT = period in seconds;

l_i = length of block i;

Dq_{ij} = number of vehicles to be transferred from block i to block j this period.

The rationale for such a formula is that mean speed is a function of density and that vehicles are assumed to be equally distributed throughout any given segment. It is apparent that this model will fail miserably where the geometry of the roadway system does not support the density-speed function employed. This type of function is generally acceptable for most situations however (see Appendix B).

Block counts are necessarily adjusted each period by subtracting the output from the block and adding the input

to the block. In any instance whereby the maximum block count is exceeded, the excess vehicles will be transferred backwards down the roadway until they are absorbed by under-saturated blocks.

The cell segments or blocks directly adjacent to the intersection (which is not a block) contain the phasing scheme attributes as well as the stochastic turn properties of the traffic stream. When signals or vehicular conditions do not permit vehicle transfer, the adjacent intersection block sets transfer quantities out of the block equal to zero. Quantities of turners (left and right) are maintained in the block and turner transfers are accomplished by the standard formula. Gap analysis is incorporated by checking the output from a block containing possibly conflicting vehicles. If this output is zero the waiting vehicles can continue, otherwise they continue to wait. It is noticed that this type of gap analysis is relatively slow in transferring vehicles in comparison to the real situation. This could possibly be somewhat alleviated by a more microscopic breakdown of the roadway in the neighborhood of the intersection.

Vehicles are generated at input links of the system according to a Poisson distribution and are considered homogeneous throughout. Reaction and acceleration factors are partially compensated for by the phasing systems (ie green comes on effectively some compensation time later than

actually) but no consideration is given for the following possibility: a right turn lane has a straight through vehicle delaying turners which could be moving on a red light or a turn arrow. Although such delays could soon be significant, they are not considered here.

Statistical measures accounted for in the model include the system input-output rates, the average density of vehicles in the system (this is calculated for every period by Sum q_i/Sum Q_i), the average speed of vehicles throughout the system and the build up of queues at intersections. A somewhat novel feature is used in evaluating mean vehicle speed for the system. Provision is made for remembering the position of a single test vehicle within each block. This vehicle is moved with the flow, its relative position in a block always being remembered, by the conventional flow or transfer equations. By inserting this test vehicle for a number of runs a reasonable estimate of mean vehicle speed throughout the system can be obtained.

Validation of this model is accomplished by actually making a series of test drives through the real system and comparing these results with simulated data. Further indications of realism can, of course, be derived by comparing real and simulated queue statistics.

This study evaluates the phasing scheme of a downtown section of Kyoto, Japan. The area includes two three-way intersections, a pair of one way streets and several input

and output ports and is therefore quite representative of a wide range of situations. A traffic board, which is a physical configuration of lamps and wires, is used in the optimization process. The lamps have a refresher time of less than five milliseconds and are hooked, via some interface, to the simulating digital computer. Vehicle motion is well illustrated by the flashing lamps. Unnecessary congestion is readily observed and can be compensated for in the phasing scheme. Using this traffic board and the simulation measures of performance, optimization becomes very meaningful. The authors suggest that a delay time of up to twenty seconds can be alleviated by adjusting the phasing schemes in the downtown area.

Once again core is suggested as a possible limitation for traffic flow simulation but the aforementioned area is readily simulated on a 16K machine with a real time to run time ratio of two to one.

Gerlough, using basically the same approach, describes the simulation of a network of eight signalised intersections. This model shows a delay reduction of ten percent, during peak hour periods, simply by adjusting the phasing schemes. No mention is given as to the size or power of the machine but the real to run time ratio is reported as five to one.

A macroscopic simulation method, using an event scan technique, is proposed by Wortham and Baker.[17] This

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[17] A.W. Wortham, and R.L. Baker, "A Macroscopic Event Scan Method of Simulating Traffic Flow in a Network", Traffic Engineering (Nov. 1968), 42.

approach is as yet in its infancy but is a radical departure from the methods currently in use. The approach is based on a single vehicle multi-interference concept which states that interference to flow for any vehicle between two points in a traffic network can be represented by mathematical equations or statistical distributions. To evaluate such a system, a single vehicle is passed through many times, its performance being recorded and averaged. Alternative policies are then implemented and the vehicle again subjected to the network. The obvious advantage in this approach is both computer space and time. The disadvantage of course lies in establishing reliable interference models or distributions.

In conclusion macro-models are desirable on the basis of core and speed and are particularly applicable to a large network where slight error is negligible, whereas micro-models are space and time consuming but are excellent in terms of detail and realism. It would seem also that micro-models tend to nurture understanding more than do macro-models.

Chapter III presents a micro-model implemented in a simulation language.

CHAPTER III

MODEL DEVELOPMENT

3.1 A Priori Consideration

Since the majority of analytical and simulation models of intersections are rigid and at least inadequate in the representation of vehicle arrivals during peak hours, it was decided to formulate a microscopic simulation model with some flexibility in this area. It is generally agreed that arrivals at intersections, which are not directly influenced by other intersections or bottlenecks, can be reliably represented by the Poisson distribution. It is obvious that the majority of intersections are not isolated to this extent. It is also obvious that the main bottlenecking influence on most urban intersections is neighboring intersections. Queued vehicles are discharged from intersections in groups with more or less constant headways. These groups constitute what are known as platoons and endure until the queues are deleted. The constancy of intra-platoon headways depreciates with increasing distance from the discharge point as individual driver-vehicle characteristics emerge until finally the platoon is no longer discernable and the vehicle distribution is once again random. In situations where the distance of separation of intersections is not sufficient to "re-randomize" the traffic, platoon behavior must be considered. It seems desirable then, that an intersection model be

capable of accounting for at least both random and platoon arrival rates.

This newly conceived model is intended as a tool to assist the traffic engineer. Therefore it should be constructed in such a way that the engineer does not need to know a great deal about simulation, or about computers, in order to use it effectively. This implies that the model must be flexible enough to require few or no alterations to simulate a variety of intersections and also requires that the model accept intersection input specifications in terms familiar to the traffic engineer.

Finally, since the model is to be used extensively in decision making, it must be realistic and accurate and it must be economical.

3.2 Planning Decisions

In the light of the above considerations, one is in a position to choose the programming language most suited for the task. A simulation language is most desirable for two reasons - it reduces the programmers "busy work" by a significant factor and it allows the model to be constructed in a notation more easily identifiable with the discipline. Comparing the advantages of several simulation languages available, Teichroew and Lubin conclude that; "Usually the user will be forced to use a simulation package made

available by his computing facility."[18] Thus the language General Puspose Simulation System/360 was chosen for model implementation.

3.2.1 General Purpose Simulation System/360

A system can be defined as a set of entities united by some form of interaction or interdependence. G.P.S.S./360 is a general purpose system simulation package providing for four types of such entities. These entities are classified as (1) dynamic, (2) equipment, (3) operational, and (4) statistical.

The dynamic entities of G.P.S.S./360 are called transactions. They represent units of traffic in a system such as people in a queue, ships in a harbour, or automobiles on a roadway. These transactions are created and destroyed as required during a simulation run (created upon entry into the system and destroyed upon departure) and can be thought of as causing actions to occur while moving through the system. Associated with each transaction, in memorandum notation, is up to one hundred and twenty-seven full or halfword integer parameters which can be assigned values by the user to represent characteristics of the transaction. For example, a transaction representing a vehicle on a road-

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[18] Daniel Teichroew, and John Francis Lubin, "Computer Simulation - Discussion of the Technique and Comparison of Languages," <u>Communications of the A.C.M.</u>, IX (October, 1966), 738.

way may have speed, maximum acceleration, and target free flow velocity as parameters. These attributes are then used in the simulation logic to determine transaction performance - for example determine the travel time between two specified points for a vehicle transaction.

Entities of the second class represent elements of system equipment that are acted upon by transactions. These include "facilities", "storages" and "logic switches". A facility can handle only one transaction at a time, and could represent a box office service, a single pier in a harbour, or a section of a roadway only large enough to accommodate one car. The facility therefore represents a potential bottleneck. A storage is equivalent to a group of parallel facilities and can handle several transactions concurrently. A storage could represent such things as a waiting room or a parking lot which have finite limits. The logic switches in G.P.S.S./360 are simply two state indicators which can be set and reset or inverted in order to alter the flow of transactions through the system.

The operational entities are called blocks and constitute the logic of the system, instructing the transactions where to go and what to do next. The logic blocks of G.P.S.S./360 are identifiable with common flow chart blocks and the language is often referred to as a flow chart language. There are forty-three distinct block types in G.P.S.S./360 each with a variety of options. Typical

operations include "entering" or "leaving" a storage and "seizing" or "releasing" a facility.

Statistical entities constitute the fourth and final class. These are included in order to measure system behavior or performance. Two types of statistical entities are provided: "queues" and "tables". Each queue maintains a list of transactions delayed and keeps a record of the average number of transactions delayed and the length of these delays. A table may be used to collect any sort of frequency distribution desired. Common table usage involves timing transactions through various portions of a system.

The above four entities constitute the G.P.S.S./360 language. It may be helpful at this time to also note that events or state changes are scheduled in G.P.S.S./360 and an event scan technique updates the simulator clock. The clock update, as well as the result of any calculations, is integral (G.P.S.S./360 truncates all calculations) - thus the accuracy of simulated results is controlled by the choice of the simulator to real time ratio and is the responsibility of the programmer.

3.3 Subsequent Decisions

Initial experimentation with crude traffic flow models clearly demonstrated the need for large amounts of computer time with G.P.S.S./360 - particularly with larger models. This flatly eliminated the possibility of an interactive traffic

model subject to car following equations or the like. Furthermore extensive list scanning and/or heavy computation in any form appeared formidable. Since peak hours constitute the critical traffic period, it was decided to orient the model particularly toward this time - neglecting non-peak considerations wherever the time problem was acute. Subsequent simplifying hypotheses and assumptions, some of which are equally applicable to non-peak times, include the following.

1. It is hypothesized that there exists some velocity V, which can be attributed to all queued vehicles and to all vehicles stopping at or within the intersection, such that this velocity will effectively account for all accelerations and decelerations during intersection passage. Furthermore this velocity V shall be instantaneous and subject only to a one second reaction factor and shall be common throughout all arteries of the intersection. It shall be denoted as the common constant queue discharge velocity.

2. Passing does not occur in the vicinity of the intersection, nor does lane change within the intersection. It should be noted that lane changes outside the junction are accounted for by arrival distributions. These distributions are tabulated according to the number of vehicles entering the intersection in a given lane. They therefore account for any lane changing which has occurred prior to intersection entry. These distributions do not however

account for the time that the lane changing vehicle has spent in its original queue. This idle time is usually small as most changes are made prior to queue entry.

It is obvious, from the foregoing qualifications, that no attempt is to be made to accurately simulate queue build-up. The omittence of detailed analysis of queue behavior, in favor of computer time also inhibits measuring time in queue, length of queue, number of stops, and stopped time. There measures however were shown, by Gerlough,[19] to be highly correlated* with mean system delay which is still accountable. Furthermore since driver attitudes suggest that delay time is the prime concern, the cruder performance model is deemed satisfactory. At this point it is apparent that other possible simulation features should be investigated in terms of expendibility on the basis of computer time and model realism or accuracy. It was therefore decided to construct a completely general purpose model, in accordance with the previous hypotheses, so that the effect of a variety of features could be interpreted through simulation results. Features included for evaluation are amber light treatment, accuracy provided for by relative time sizes, and arrival velocity distributions. The remainder of this chapter describes the general purpose model used for investi-

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[19] D.L. Gerlough, and F.A. Wagner, "Improved Criteria for Traffic Signals at Individual Intersections", National Cooperative Highway Research Program Report 32, (1967),71.

*Correlations are all positive (See Table A-3.1)

gation. Chapter IV presents the investigation results and the accordingly modified model.

3.4 The General Purpose Model

The general purpose traffic simulation model has been designed as a tool for the traffic engineer to assist him in evaluating traffic flow at intersections. As such the model is designed to be as flexible as possible and yet easy to use by someone unfamiliar with computers. The following section contains a general description of the model. Major input specifications are described in general terms and some consideration is given to the prominent simulator features. A more detailed listing of input specifications is included in Appendix C. This appendix also contains a description of model operation at the programming level. The purpose of the following section is to introduce the reader to model capabilities and characteristics.

3.4.1 The System

The physical system represented by the model is the orthogonal intersection of two eight lane bi-directional roadways and up to one thousand feet of approach for each artery. The junction is under the control of a variety of two, three, and four way phasing schemes and the model configuration is labelled according to direction for ease in description and application. All configuration options

are completely under user control.

Physical configuration is accepted as dimensional input to the simulator. The following specifications are required.(see Figure 3.4.1)

1. The length of the approach arteries to be included in the system (in feet). The approach portion of each artery is of equal length and this specification sets up the system boundaries. In practice, in order to optimize run time, the length of the approach should be kept as small as possible, while still accounting for maximum queue length. The system boundary limit is currently set at one thousand feet, or about forty queued vehicles for each of sixteen lanes. The "reallocate" feature of G.P.S.S./360 can be used to expand the system but requires some programming knowledge. For most cases, current limits are satisfactory.

2. The number of lanes desired in each direction. The simulator flexibility allows for approach configurations of two to four lanes in each of the four directions. It is assumed, in all cases, that exit arteries are capable of handling the approach volume.

3. The actual dimensions of the intersection - length (E-W) and width (N-S) from entry line to entry line. It is also imperative that the user specify the distances from stop line to entry line for each artery.

4. The last specification to be included as part of the physical configuration is the effective length of a

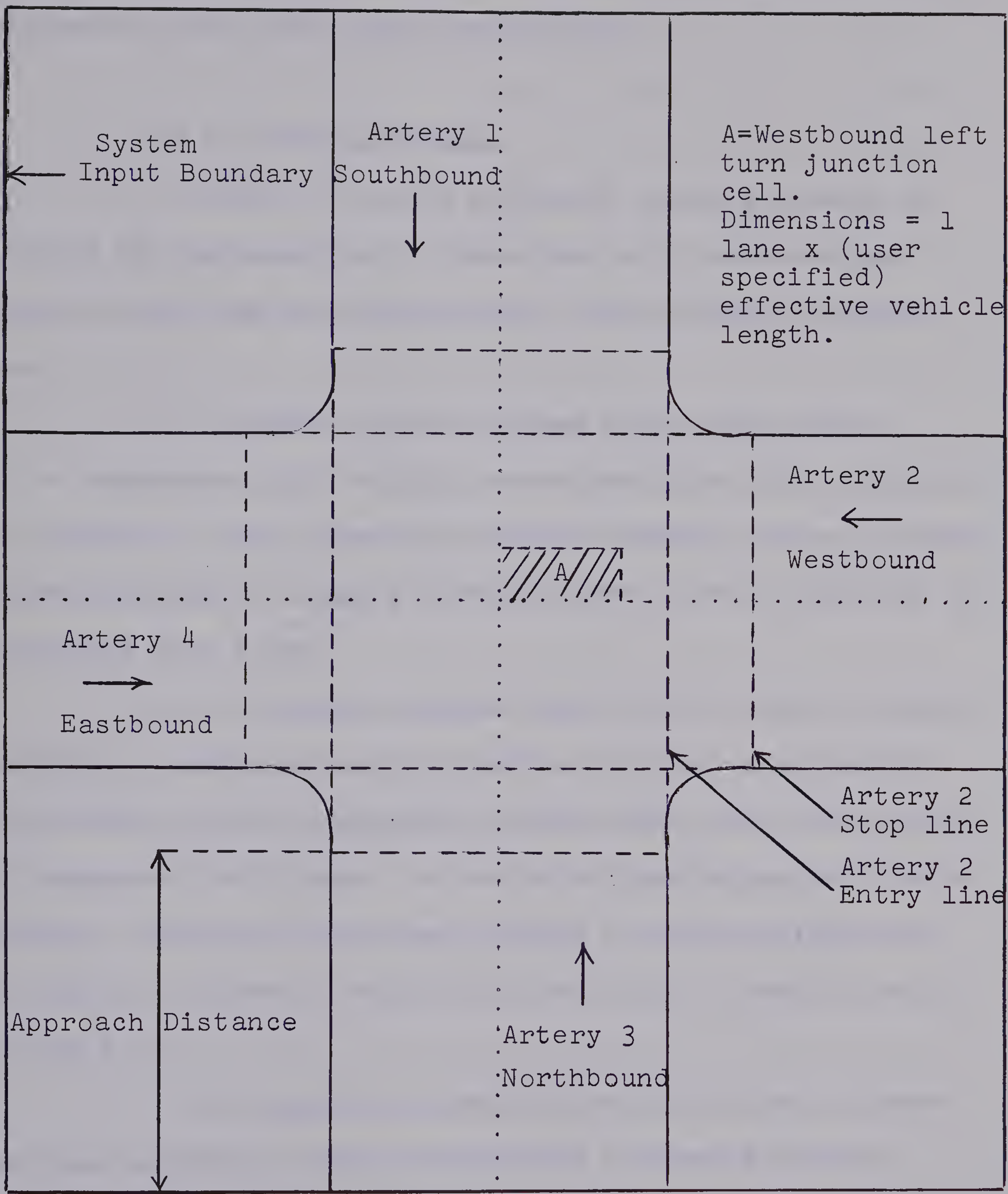

Figure 3.4.1 System Configuration

queued vehicle. This specification sets up junction cells from which left turns are accomplished.

3.4.2 Phasing Schemes

A total of eleven different phasing schemes is offered by the simulator. These are self contained and require only time specifications. The different schemes are:

1. A simple two way scheme with south bound (1) - northbound (3) traffic versus westbound (2) - eastbound (4) traffic. Both street and avenue traffic can be allotted either leading or lagging flashing green time to provide for protected left turns.

2. A three way scheme with either street (1 and 3) traffic or avenue (2 and 4) traffic flowing concurrently. With either choice, opposing streams again have the option of protected left turns. A choice of phasing cycle is also offered. Thus the three way phasing cycles available are (1 and 3),2,4, and (1 and 3),4,2, and 1,3, (2 and 4) and 1, (2 and 4),3.

3. All possible combinations of four way schemes are also offered. These include the following cycles: 1,2,3,4, and 1,2,4,3, and 1,3,2,4, and 1,3,4,2, and 1,4,2,3, and 1,4,3,2. With four way schemes all left turns are free flowing.

In all of the above configurations the duration

time for any green or amber signal must be specified in seconds. The steady green time here refers to the time during which conflicting or opposing flows are both green. Neither lead nor lag green time is included in the steady green time.

One further option is also available - that of the right turn arrow. This may be specified as on concurrently with any phase for any other given phase. That is to say that the southbound right turn arrow can be specified as operating with the green phase of westbound, eastbound or northbound traffic. All directions are included for completeness.

3.4.3 Vehicle Representation

Vehicles are generated at the system boundary according to a Poisson and/or platoon distribution on a lane by lane basis. The user who is reasonably familiar with G.P.S.S./360 has the extended option of specifying any desired distribution in place of the Poisson simply by altering a few cards. The novice however is restricted to these two distributions and a mixture thereof. The user must specify arrival characteristics in terms of mean inter-arrival times for both arrival features. More discussion of platoon implementation will follow later.

Each vehicle has associated with it four parameters - current velocity, target free flow velocity, turn indicator,

and a dummy parameter used to inhibit vehicle passing. Upon generation, vehicles are randomly tagged with a free flow velocity according to a precoded distribution. The mean for this arrival velocity distribution must be specified for each artery by the user. This free flow velocity is sustained until the vehicle encounters some blocking or restrictive condition. Blocking conditions result from overtaking slower vehicles, entering a queue, or encountering a red signal. Restrictive conditions appear only in the form of maximum turn velocities. If the condition encountered is a restriction, the vehicle is required to slow to the maximum velocity at a specified rate of deceleration and the slow time is accounted for accordingly. If the vehicle encounters a blocking condition, its velocity is immediately reassigned as the effective queue discharge velocity and the delay is implicitly accounted for by the blocking condition. Where the blocking condition of overtaking a slower vehicle exists prior to queue entry, the overtaking vehicle is effectively assigned the velocity of the blocking vehicle.

During red signals vehicles queue at the intersection stop line. At green time they are dispersed according to the headway distribution formulated by Gerlough and Wagner.[20] This distribution is essentially

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[20] Ibid., 42.

constant with a mean headway of 2.37 seconds for all vehicles and an extra second for reaction time for the first vehicle in queue. This distribution was arrived at through simulation of the dispersion of fifty queues of twenty vehicles each. Each queue was composed of a variety of vehicle-driver attributes and the results fitted well to real data. Vehicles which enter the intersection as free flowing (ie. not in queue) are not subject to queue discharge procedures. Vehicles which become blocked within the intersection, because of some turn conflict, are subject to a reaction factor of one second, before motion is resumed.

Upon the completion of intersection passage vehicle travel time and delay time are tabulated from the time at which the vehicle entered the system. Delay time is calculated by taking the difference between actual travel time and desired travel time according to the tagged free flow velocity and accounting for turn considerations. Subsequent to statistical tabulation each vehicle is terminated or destroyed.

3.4.4 Platoon Behavior

To use the platoon feature of the simulator, the traffic engineer must specify in which arteries the platoon behavior is to occur, the headway times and periods of the platoons for each artery, and the duration times of the platoons for each lane of each artery. The platoon period,

for a given artery, shall be taken to mean the time from the arrival of the first vehicle in a platoon at the system boundary to the arrival of the first vehicle in the subsequent platoon at the same boundary. Platoon duration, for a given lane, is the time from the arrival of the first vehicle in a platoon at a system boundary to the arrival of the last vehicle in the same platoon at the same boundary. For platoon behavior to be meaningful in this model, it must be predictable in period and duration. Both of these measures are taken to be constant. Since network control usually involves some degree of signal synchronization and since peak traffic volumes are relatively stable, this requirement is realistic.

It should be noted that platoon behavior, if specified for a given artery, will be common to all lanes within the artery. Thus the platoon period and arrival rate specifications (headway) apply equally for all lanes in a given direction. Each lane however is subject to a unique measure of duration. This measure of duration, in conjunction with the specified headway, directly determines the number of vehicles arriving in a platoon for a given lane. When the platoon is exhausted, for any particular lane, the simulator reverts to the Poisson arrival rate for the remainder of the platoon cycle.

In the real situation platoon behavior may exist in some or all of the approach arteries. The arrival of these

"arterial platoons" at the system boundary may or may not be in phase. A further user specification is required to correctly phase these platoons with respect to one another and with respect to the phasing scheme. Referring, momentarily, back to the section on phasing schemes, it can be noticed that all cycles begin with artery 1 or artery 1 and artery 3. This is done intentionally in order to provide an initial real reference for platoon offsets. If arteries 1 and 3 are flowing concurrently and the phasing scheme provides artery 3 with a leading flashing green, the beginning of this flashing green denotes the real reference point. In all other cases the reference is to be taken as the flashing or steady green of artery 1. Platoon offset specifications merely denote the time lapse from the reference point to the arrival of the various platoons at the system boundaries. These offsets serve only to initialize platoon arrivals and the offsets are thereafter sustained by the individual platoon periods. For a more detailed description of platoon behavior logic, refer to Appendix C.

3.4.5 Amber Signal Decisions

The method used to incorporate response decisions to the amber signal is based on the probability distributions of real data derived by Olson and Rothery[21] and Blackman

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[21] D.L. Olson, and R.W. Rothery, "Driver Response to the Amber Phase of Traffic Signals, "Traffic Engineering, XXXII (1962), 17.

and Crawford.[22] These distributions evaluated the probability of stopping as a function of the time and/or distance from the intersection when the signal went amber. Gerlough and Wagner[23] plotted these field data findings against deceleration required to stop and found the fit very satisfactory. The following probability table emerged as a result of their efforts.

AMBER DECISION PROBABILITY TABLE

Acceleration Required to Stop at Stop Line (ft/sec^2)	Probability of Stopping
- 0 to - 0.99	1.000
- 1.00 - 1.99	0.994
- 2.00 - 2.99	0.989
- 3.00 - 3.99	0.982
- 4.00 - 4.99	0.972
- 5.00 - 5.99	0.956
- 6.00 - 6.99	0.935
- 7.00 - 7.99	0.905
- 8.00 - 8.99	0.867
- 9.00 - 9.99	0.820
-10.00 -10.99	0.762
-11.00 -11.99	0.700
-12.00 -12.99	0.624
-13.00 -13.99	0.548
-14.00 -14.99	0.468
-15.00 -15.99	0.390
-16.00 -16.99	0.318
-17.00 -17.99	0.250
-18.00 -18.99	0.190
-19.00 -19.99	0.140

Table 3.4.5.1

[22] A.R. Blackman, and A. Crawford, "Driver Behavior During Amber Period of Traffic Lights: 6 Road Observations", Unpublished Research, British Road Research Lab (May, 1962).

[23] D.L. Gerlough, and F.A. Wagner, "Improved Criteria for Traffic Signals at Individual Intersections", National Cooperative Highway Research Program Report 32, (1967),71.

This model directly incorporates the table in the amber decision routine. The user specification required is the length of the amber signal for all arteries.

This decision routine is encountered by a vehicle only when the signal is amber and when the position of the vehicle is concurrent with the stop line. At this time it is determined how long the amber signal has been on. Since the vehicle speed is constant (by hypothesis), the deceleration required to stop, at the time the signal went amber, is easily calculated. Note that no consideration is given for reaction time in the calculations because a one second reaction factor is implicit in the probability function.

Left turners constitute an extra problem in the amber decision routine. It is quite common, in real situations for vehicles to be stopped at the stop line when the signal goes amber because of a blocking condition. In most cases such vehicles remain stopped. For left turn lanes the model checks for such conditions. The G.P.S.S./360 transaction has an implicit delay indicator which can be examined to determine if a blocking condition exists or has existed without any subsequent motion. If a blocking condition prevails during the amber phase, the vehicle remains stopped and the decision function is bypassed. Otherwise the decision function is normally employed.

Right turners in all situations are assumed to automatically initiate turns during the amber signal phase.

3.4.6 Turn Features

All turn times are evaluated according to turn lengths and maximum turn velocities. The user must therefore specify the lengths of all left and right turns in the system, from stop line to stop line, and the respective maximum turn velocities. It should be noted here that delayed and free flowing left turners are assumed to follow the same path. Input specifications are also required to provide the percentage of turners in each turn lane. Turners are probabilistically tagged as such and free flowing turners are subject to slowing motion if their velocity exceeds the maximum. In this fashion free-flow turners do not constitute a problem. On the other hand blocked turns do. If delayed left turns and right turns against red lights are not realistically represented, large discrepancies between real and simulated data can easily result. Both types of turns involve a driver analysis of possibly conflicting traffic and a subsequent decision either accepting or rejecting turn possibilities. Field data has been gathered in this respect and Kell[24] and Ehle[25] present probability distributions of gap time versus gap acceptance. Ehle's distribution yields a mean gap acceptance time of 7.16 seconds whereas that of

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[24] J.H. Kell, "Analysing Vehicular Delay at Intersections Through Simulation", Highway Research Board Bulletin 356, (1962),28-39.

[25] B.L. Ehle, "On Gap Utilization", Traffic Engineering, (Oct. 1967),38.

Kell's yields 4.59 seconds. It would appear that different approaches perhaps considering reaction factors, were used in the latter case. Since Kell's data has been used successfully in intersection simulation[26], 4.59 seconds is the mean gap acceptance time used in the model.

The implemented gap acceptance feature is common to both right and left turners. In essence, the method used here is to define a section of roadway relative to a given turner such that the turner will always proceed when this section is free of cars and that the turner will always wait when the section is not free of cars. This section of roadway will be defined from the point P, where P is determined by the mean gap acceptance value and the speed of the oncoming vehicles (see diagram 3.4.6.1). Exceptions that must be considered include the possibility of the "conflict zone" containing only cars that are blocked by delayed left turners, and/or containing only turning, therefore non-conflicting vehicles.

These considerations are treated respectively as follows: The previously defined conflict zone is subdivided into two parts. One part represents only the inside lane of the oncoming roadway. (This is shown as the shaded area (A) in the diagram). The other shaded part (B) represents the

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[26]D.L. Gerlough and F.A. Wagner, "Improved Criteria for Traffic Signals at Individual Intersections", National Cooperative Highway Research Program Report 32, (1967),45.

remainder of the original left turn conflict zone. If either of these portions of the roadway is free of vehicles, the waiting left turner C will proceed. On the other hand if area A is occupied by blocked vehicles and area B is free, turner C will also proceed. Diagram 3.4.1 denotes a shaded left turn junction cell which will be occupied by any west-bound left turner. This type of junction cell is common to all arteries and blocked inside lane vehicles are evident when this area is occupied. Left turner C will now proceed when area A and area B is free of vehicles or when area B is free of cars and the left turn junction cell within A is occupied. It remains to consider the condition whereby the conflict zone contains only turning vehicles.

Waiting left turners, such as C, can only distinguish approaching turners from approaching non-turners, in A or B, by turn signal or by turn behavior. In real situations the turn signal is often neglected. Furthermore it can be noticed that signalling vehicles do not always turn. This type of real behavior limits the real distinguishing feature to observable turn behavior. For these reasons, it is appropriate to remove turners from the conflict zone only when they enter the turn area (ie. cross the approach stop line). The simulator does account for the driver analysis of this "turner only" gap condition in this fashion.

The same above complete gap analysis is awarded the right turners in the system. For a "red light turner", such

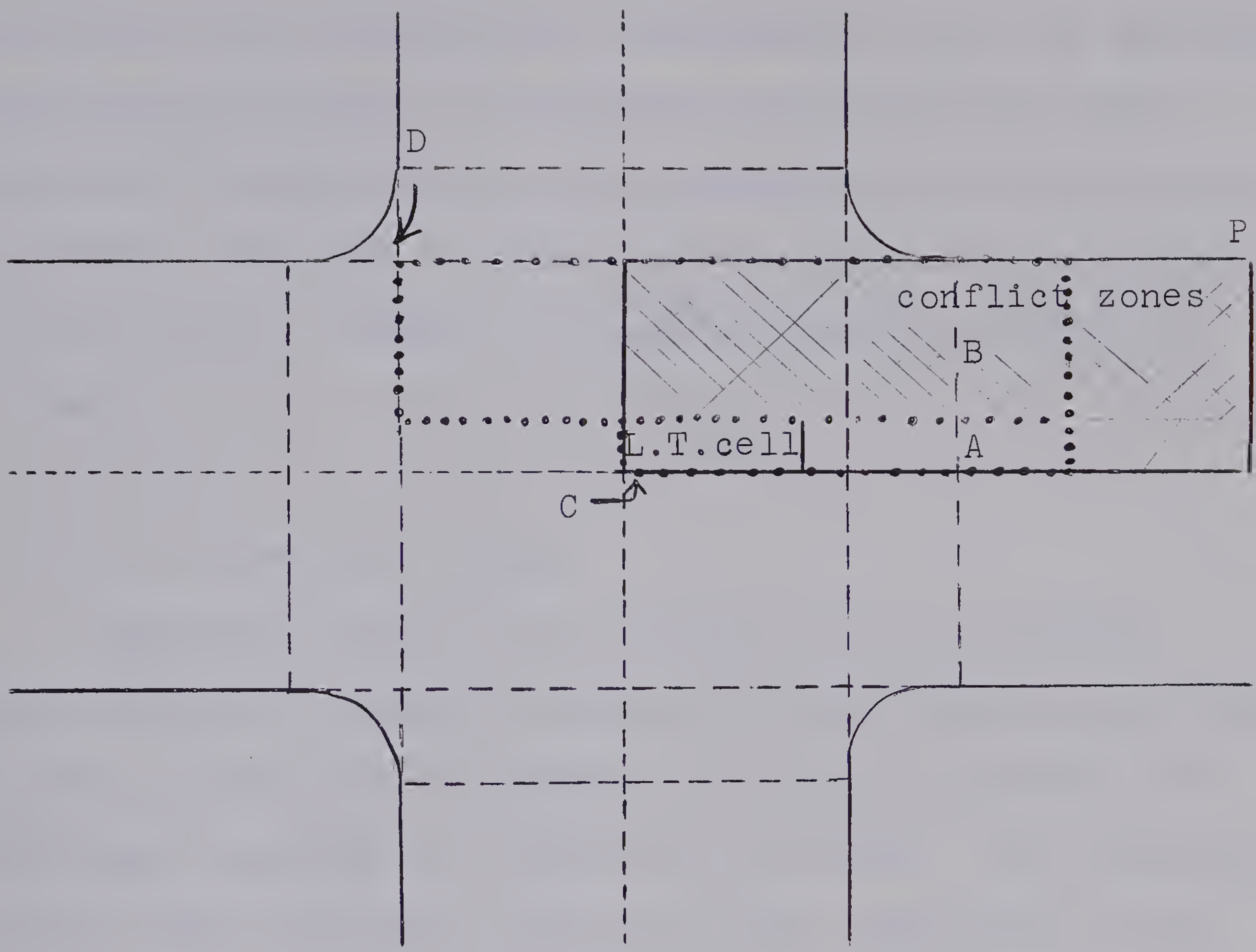

Figure 3.4.6.1 Turn Conflict Zones

as D, the conflict zones accounted for are shown by the heavy dotted line.

In all pending turn situations, signal changes override gap analysis. This is to say that the waiting turner C will proceed immediately when the signal turns amber and that waiting turner D will proceed on green or a green arrow.

The conflict zones in the model are represented by variable "storages". The dimensions of these storages are

dynamically allocated for each artery of the intersection according to the intersection configuration and the specified mean arrival velocity. The delayed left turn zones are "facilities" which can only be occupied by one vehicle each at a time. The size of these junction cells is determined by the effective length of a queued vehicle specified by the user.

3.4.7 Pedestrian Delays

Pedestrian delays are accounted for in the model. These delays are assumed constant for each signal phase and the user is required to specify the time, in seconds, for which each crosswalk is effectively occupied. The simulator effects these specified delays from the beginning of each green and both right and left turners are delayed accordingly. Right turners are subject to delay at both conflicting cross-walks and subsequent queues are held up until the leading vehicle can proceed. Left turning vehicles encounter pedestrian delays at the turn conflict zone and consideration is given to the subsequent queue impedance.

3.4.8 Statistics

Statistical measures provided for in the model are time in system and system delay. These measures are gathered in frequency tables and all tables, including means and standard deviations, are available to the user as standard

output. Separate tables are provided for each artery so that the equalization of delay policy can be easily employed.

Using this general purpose model, a variety of simulation runs were undertaken to indicate the degree of detail required in the simulation of intersections. The results of these runs for a typical intersection are given in the following chapter along with the appropriate modifications to the model.

CHAPTER IV

VALIDATION AND REFINEMENT

4.1 Model Validation

Model realism was confirmed by comparing simulated and real measures of mean travel time through the system for two intersections*. These comparisons were made under conditions exhibiting non-platooned, light platooned and heavy platooned traffic. Each comparison was made for a half hour period and all real data was gathered during the afternoon peak hour.

Real data was obtained by one second time-lapse photography. Technical problems and the lack of vantage points restricted reliable analysis to three approach arteries individually. Since the simulator logic of each artery is exactly the same this restriction is not really detrimental. The only potential demerit is the simulation of right turns on red lights. (The no chance indicators of the left turn lanes preserve the realism of the left turn situation). In validation, oncoming, possibly conflicting traffic was treated as random. Since the volume of traffic at this time is substantial, the error introduced by this assumption is negligible. In order to further eliminate any source of error extra routines were added to the program to provide individual lane statistics for the arteries tested. The comparisons of the real and simulated data for the three arteries appear below.

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* For actual locations see Appendix D.

REAL-SIMULATED TRAVEL TIMES

Lane Number	Lane Type	Arrival Characteristics	Real Mean Travel Time	Simulated Mean Travel Time
1	Right Turn*	Random	16 sec.	16 sec.
2	No Turn	P-R**	28 sec.	31 sec.
3	No Turn	Random	29 sec.	25 sec.
4	Left Turn	Random	46 sec.	45 sec.
5	Right Turn*	Random	18 sec.	18 sec.
7	No Turn	Platoons	17 sec.	18 sec.
8	Left Turn*	Platoons	22 sec.	53 sec.
13	Right Turn*	Random	15 sec.	15 sec.
15	No Turn	Platoons	13 sec.	13 sec.
16	Left Turn*	Random	15 sec.	19 sec.

Table 4.1.1

*denotes that "no turn" is optional in this lane.

** denotes that the arrival characteristics changed from platooned arrivals to random arrivals in the real situation. The simulation accordingly was adjusted from platoon arrivals, of eight vehicles each, to completely random arrivals and the above comparison accounts for the overall mean of the composite run.

Lane 15 platoons consist of eight vehicles each for the duration of the run time where lane 7 platoons consist of nine vehicles. Both lane 7 and lane 15 platoons had constant inter-arrival times of three seconds. Lane 8 platoons consist of three vehicles each and the constant

platoon inter-arrival time is two seconds.

The relationship between the real mean travel time and the simulated mean travel time is much better than expected. Although simulation results are usually interpreted qualitatively, the indication of mean error adds substantially to such judgement. It is the author's opinion that the simulator produces excellent results. With one exception the mean error between real and simulated data is 1.4 seconds. Thus the simulator is shown to realistically represent the real situation for a total of 1181 vehicles in nine different lanes under a variety of conditions.

The only exception to the high correlation occurs in lane eight in Table 4.1.1 which can be explained by an unusual intersection situation. In this real situation the geometry of the intersection and the nature of the opposing flow is such that several delayed left turners in lane eight occupy a position within the intersection such that they fail to block subsequent non-turning vehicles. Consequently several vehicles are getting through the intersection which would normally be blocked by left turners. In the current version of the simulator this action can only be represented by a lane change which is accounted for by arrival distributions. Since lane changes were often not necessary in the real situation to get around blocking left turners, this type of passing is not realistically accounted for.

A second factor which appears to contribute to the

deviation is driver foresight. The decision of drivers to stay or not to stay within lane eight seems to be based not only on the length of queue but also on the status of the signal. This particular lane is subject to a leading flashing green and the decision to change lanes appears to be influenced by this factor. Although the platoon handling routines can handle this behavior for the most part, that part of the traffic stream represented by random arrivals is not under any such control.

Furthermore since this real data was gathered during exceptionally heavy flow (a transit strike situation), allowing even three or four vehicles through instead of blocking them results in much shorter queues in the real situation.

Even so, since the optimization of delay policy involves equalizing delay among arteries rather than among lanes, the above error taken into account for the mean travel time of the overall artery produces only a net error of nine seconds. The reduction of error occurs because of the relatively small number of vehicles arriving in lane eight with respect to the total number of arrivals in the whole artery. Considering that it is not unusual for controllers to vary up to as much as four seconds in a given cycle, the error becomes less significant. However a further refinement to the simulator to accurately account for this condition is suggested as follows.

If the above situation cannot be considered atypical, the simulation model can be extended to overcome the problem by including a third left turn junction cell. This cell would be located at the edge of the curb or street divider and extend into the area of oncoming, inside lane traffic. The decision to move into this third left turn junction cell could be implemented on a probabilistic basis possibly considering the frequency of arrivals in the oncoming lane and the percentage of turners. The logic would also have to be extended such that oncoming through vehicles would be delayed by left turners occupying the third junction cell. It is suggested that this type of situation will not exist at most intersections.

4.2 Model Refinement

After validation, the model was tested according to the features outlined in Chapter III. The simulations were carried out on a control intersection using real data for a period of thirty minutes of real time. The control intersection consisted of a total of sixteen approach lanes. The results of the tests are shown below.

It should be noted that the random number generator may be responsible for some of the discrepancies observed in the tables below. In general, in G.P.S.S./360, it is possible to reset the random number generator at the conclusion of each run and produce identical generation sequences.

EVALUATION OF SIMULATOR FEATURES

Model Configuration	Simulated Travel Time	Simulated Delay Time	Vehicles Through	Real to Computer Time Ratio
Control Model with 4 simulator units = 1 second.	32.5 sec.	19.8 sec.	1748	11:1
Complete Model with 1 simulator unit = 1 second.	29.8 sec.	16.5 sec.	1805	13:1
Complete Model with no amber decision routine.	31.8 sec.	18.9 sec.	1730	11:1
Stripped Model with no velocity distribution.	26.8 sec.	15.4 sec.	1708	13:1

Table 4.2.1

In this case however this feature has been relinquished in favor of the "SAVE" feature which allows the user to bypass the lengthy assembly of the G.P.S.S./360 for each run.

In accordance with the test results, a copy of both the complete model and the stripped model have been retained. The amber decision routine has not been discarded and the variable time ratios are included in both. Once again the only difference in the two programs is that the stripped model assigns every vehicle in a given artery a user specified velocity whereas the complete model assigns vehicle velocities according to a normal distribution about the user specified mean. To conclusively sum up the relative merit

of the two models, a dummy simulation of an intersection with only eight approach lanes was undertaken. The results are contained in the following table.

COMPLETE-STRIPPED MODEL RUN TIMES

Model Configuration	Simulated Travel Time	Simulated Delay Time	Vehicles Through	Real to Computer Time Ratio
Complete Model 4 simulator units = 1 second.	31	18	538	15:1
Complete Model 1 simulator unit = 1 second.	29	17	516	16:1
Stripped Model 4 simulator units = 1 second.	33	21	523	17:1
Stripped Model 1 simulator unit = 1 second.	35	23	514	18:1

Table 4.2.2

4.3 Observations

During the validation process several significant simulator features emerged time and again. Two of these features can be classified as ease-in-application and flexibility. Two typical examples are as follows.

For testing, real data was used as simulator input. Arrival characteristics were intuitively deduced from the measured data and no statistical tests of goodness of fit

were used. This was done specifically to point out the ease with which input statistics can be gathered and implemented. The closeness of most of the above comparisons substantiate this claim.

A further simulator feature is the ease with which varying arrival characteristics can be simulated. For example, during one observation real behavior changed from platoon behavior in one of four lanes to non-platoon behavior in all lanes. This change was rather abrupt but was easily simulated by a single computer run. The technique used to simulate this changing condition is explained in the following paragraph.

In order to simulate changing conditions the following input format should be observed.

```
Initial Parameters
START 1, NP
Secondary Parameters
START 1
END
```

Figure 4.3.1 Deck Structure for Changing Conditions

The simulator reads in the initial parameters and executes the simulation according to the new condition for as long as is specified. The simulator then stops, reads in

the secondary parameters and continues the simulation - still accumulating statistics, again for a long as was specified. This process is limited only by computer time, and any of the user options such as model distributions (velocity and arrival) can be redefined in these successive steps. In order to change from platoon to non-platoon behavior, the parameters of platoon duration are set to zero in the secondary initialization. (The parameters of platoon period cannot be altered in this situation). It should be noted that this breakdown can be accomplished successively to any desired level of detail. Since platoon routines are set up during initialization, this process cannot be reversed. In summation the model is extremely flexible at any level.

Another feature of the simulator, which is considered to be of paramount importance, is its efficiency in terms of computer time and user effort.

User effort is minimized by the simple, straightforward approach of the simulator. This approach enables the traffic engineer to readily specify observed, expected or hypothetical traffic streams and to easily test the effects of proposed phasing schemes, in terms of mean system delay, on such traffic. This user feature is especially important when considering the effect of driver reaction to changes in phasing schemes. For example a change of route because of an exceptionally long left turn delay which has been effected by the abolishment of a protected left turn in favor of a

phasing scheme with a significant delay reduction for overall traffic. Similarly this minimal user effort paves the way for network optimization as outlined below.

Considering the computer time aspect of the simulator, it is extremely efficient - much more so than any simulation package heretofore advertised. This efficiency can still be further enhanced by the judicious application of the program. For example the G.P.S.S./360 monitor, in conjunction with the Urban Traffic Simulator, is approximately sixty percent I/O* bound on an individual two minute computer run (approximately thirty minutes of simulated time depending on the intersection configuration). The only I/O tasks in the model are reading in the model from tape, reading in the input deck, saving the model in its current state on tape and producing the output listing. Since the input deck and output listing are extremely compact, the "READ" and "SAVE" commands use a great deal of the computer time required for a thirty minute simulation run. Thus it is suggested that runs be made in tandem and in this way avoid the computer time wasted by executing successive "READ" and "SAVE" instructions. It should be noted that the "READ" card is only required to bring the model into core and to read in the first data set which ends with the first "START 1" card encountered. Furthermore it should be noted that if continuation runs are not required, the "SAVE" command can be omitted completely. To illustrate the effectiveness of a tandem run, the same

* I/O is the abbreviation for Input/Output.

program was run once for a thirty minute job, then twice in tandem for two thirty minute jobs. The ratios of real time simulated to computer time required were 15:1 and 25:1 respectively. As the simulation time rises in the tandem run,the I/O time remains almost the same and the overall efficiency of the run increases greatly. This increase will be continually realized as the length of the tandem run increases. Since most jobs require several simulations, with a variety of parameters, the tandem run appears desirable from the users point of view. Input can be handled in one deck and comparisons of phasing schemes done by thumbing through only one listing. This is indeed a rare case whereby less user effort produces greater system efficiency.

Network Simulation - Combining the above simulator attributes of flexibility, accuracy, ease of operation and efficiency with the ability to handle platoon arrival rates and the ability to extend the approach arteries to the discharge boundaries of neighboring intersections, it becomes possible and practical to attempt network optimization on an intersection by intersection basis. By choosing a starting intersection, the engineer can optimize vehicle flow through this intersection by varying the phasing schemes. Using the equalization of delay policy, this optimization should not be difficult. When optimization has been achieved for this intersection, its output characteristics (platooned or

random departures) can be deduced from the simulation* or from the real situation and used as arrival characteristics for the simulation of neighboring intersections. Because the simulator is capable of handling platoon and/or random arrivals, vehicle flow from one intersection to the next can realistically be accounted for. In this step by step fashion network optimization can be achieved with a minimum of computer time and space and a minimum of extra user effort.

All in all the observations conclusively demonstrate the merit of the relatively simple, reasonably accurate, and exceptionally efficient Urban Traffic Simulator. With this program the traffic engineer, even a computer novice, can simulate a variety of real and hypothetical traffic situations and through such simulation not only arrive at optimum phasing schemes for intersections and networks of intersections, but also gain a great deal of insight into the nature of traffic flow in the process.

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*In order to have a printout of the departure rate, the current model would require the addition of table statistics to each of the discharge lanes. Platoons can currently be deduced from the optimum green time and the queue statistics which are currently available as special output.

CHAPTER V

CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

At this point the objectives of the project have been realized. It has been shown that it is possible to realistically simulate vehicle flow through intersections using a common, constant queue discharge velocity. The general purpose simulator has been constructed on this principle. The simulator has been designed so that the traffic engineer with very little computer knowledge and very little extra work can take the normally available traffic flow statistics and run the simulator with up to four approach lanes in any direction. From the simulation results he can evaluate various phasing schemes and thus implement the best phasing scheme to minimize system delay. Furthermore it has been shown that the simulator is extremely efficient in terms of both computer time and user effort. Finally the simulator is useful as a tool because of its flexibility and ease of operation.

5.2 Future Research

Projects which could well be considered as worthwhile in the simulation of traffic flow are as follows.

One could embark upon a macro simulation of city streets using G.P.S.S./360 storages as road segments and the filter

sequencing technique employed in this model. In this way vehicle transit times could be accurately measured by system parameters rather than by the floating car technique currently used in most macroscopic simulations.

A second project is the implementation of the multi-interference simulation model as proposed by Wortham and Baker.[27] This would necessarily involve the compilation of large amounts of statistics for many intersections. These could possibly be gathered by interfacing vehicle counters with selector channels, via telephone lines, and tabulating the statistics on line in real time. Such a procedure would result in a fund of accurate statistics for simulation as well as provide the traffic engineer with a highly sophisticated traffic survey.

A desirable task which is completely computer oriented is the adaption of G.P.S.S./360 to include communication facilities within itself and between itself and the user. As it exists now, transaction parameters cannot be scanned or referenced in any way by other transactions. The user-machine communication is also entirely one way. The user can specify input to the simulation system but the system is powerless to respond dynamically in any fashion. Because of these two features, completely interactive models are

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[27] A.W. Wortham, and R.L. Baker, "A macroscopic Event Scan Method of Simulating Traffic Flow in a Network", Traffic Engineering (Nov. 1968), 43.

almost impossible - at the very least completely inefficient. It is suggested that a reasonable amount of effort in this direction could increase the power and value of the General Purpose Simulation System/360 immeasurably.

A final project, which would be extremely large, is the development of a traffic simulator interfaced with a graphical display system. In this way vehicle flow, either on a micro or macro level, could be readily observed and corresponding adjustments made to the simulated controllers immediately. In this "seeing is believing" fashion, optimization becomes very meaningful. Furthermore it seems that some form of man-machine symbiosis is usually more meaningful than batch processing in any context.

In closing I pose one final thought. Consider the possibility of developing a simulation program which operates on a iterative-convergent technique. This model would only require one user initialization in the form of real data input and would proceed to optimization by itself. Such a technique appears to be the next plateau in any type of simulation.

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APPENDICES

APPENDIX A

A-1 Leader-Follower Equations of Motion

Both leader and follower equations of motion have the general form

response = sensitivity x stimulus

For leaders, the stimulus can be taken to be the difference between actual velocity and the desired target velocity. Thus in the free flow equations

$$Acc(J,I+T) = K[TVEL(J) - VEL(J,I)]$$

the measure of sensitivity is the proportionality coefficient K. The purpose of this coefficient is to interpret or scale driver response to the dissonant velocity conditions. Thus the proportionality coefficient is a measure of driver behavior, within real restrictions such as maximum vehicle acceleration, and is difficult to measure in the field. Gerlough and Wagner evaluated K by comparing simulated vehicle motion with real data. Close agreement was obtained with a K value of 0.5 sec^{-1} and a maximum acceleration of $6'/sec^2$.

Note that this free flow equation is not applicable for stopping.

For followers, the stimulus is taken to be the difference in speeds between the follower and his immediate leader. The sensitivity of this stimulus is a function

of two factors - the characteristic speed of the traffic stream and the distance of separation of the leader and the follower. Thus in the car following equation

$$\mathrm{Acc}(J+1,I+T) = \frac{\mathrm{Ao}[\mathrm{Vel}(J,I)-\mathrm{Vel}(J+1,I)]}{\mathrm{Pos}(J,I)-\mathrm{Pos}(J+1,I)}$$

the response is dictated by the reciprocal spacing of the two vehicles and the characteristic speed (Ao) of the traffic stream.

It should be understood that Ao does not correspond to the target of free flow around which vehicles center, but is the typical speed past the entry point (or point of maximum flow) of vehicles that started as part of a long stationary queue once maximum flow has been attained.

Since Ao corresponds to maximum flow, the reciprocal spacing model is compatible with the steady state relationship of the traffic stream. This relationship has the general form

$$q = ku$$

where

q = mean flow;

k = mean concentration;

u = mean speed.

For conditions of maximum flow

$$\frac{dq}{dk} = u + k\frac{du}{dk} = 0.$$

At this condition u = Ao, by definition. Therefore

$$Ao = -k\frac{du}{dk}$$

and

$$\frac{du}{Ao} = -\frac{dk}{k} .$$

Integrating gives

$$u/Ao = -\ln(k)+C .$$

For the traffic stream mean flow is equal to zero at jam concentration. Therefore the boundary conditions are

$$u = o, \ k = k_j .$$

Thus $C = \ln(k_j)$ and the steady state equation becomes

$$q = Aok\ln(k_j/k) .$$

The concentration and flow are measurable for any intersection. The calculation of Ao then becomes trivial. A typical value for Ao is about 30'/sec.

A-2 Probability Distributions

The following three tables are the probability distributions employed in Gerlough's simulation. The difference between gap and lag should be mentioned at this time. Both refer to spacing between vehicles but each is from a different perspective. In the simulation model, each driver initially analyzes the possibility of a left turn at the beginning of the turn area. From this perspective the

AMBER DECISION PROBABILITY

Acceleration required to stop at stop line (ft/sec^2)		Probability of stopping
- 0	to - 0.99	1.000
- 1.00	- 1.99	0.994
- 2.00	- 2.99	0.989
- 3.00	- 3.99	0.982
- 4.00	- 4.99	0.972
- 5.00	- 5.99	0.956
- 6.00	- 6.99	0.935
- 7.00	- 7.99	0.905
- 8.00	- 8.99	0.867
- 9.00	- 9.99	0.820
-10.00	-10.99	0.762
-11.00	-11.99	0.700
-12.00	-12.99	0.624
-13.00	-13.99	0.548
-14.00	-14.99	0.468
-15.00	-15.99	0.390
-16.00	-16.99	0.318
-17.00	-17.99	0.250
-18.00	-18.99	0.190
-19.00	-19.99	0.140

Table A-2.1

LEFT-TURN DECISION PROBABILITY

Lag or Gap Size (sec)	Probability of Accepting Lag	Probability of Accepting Gap
0 to 0.5	0	0
0.5 to 1.0	0	0
1.0 to 1.5	0	0
1.5 to 2.0	0	0
2.0 to 2.5	0	0
2.5 to 3.0	0	0
3.0 to 3.5	0.030	0.150
3.5 to 4.0	0.124	0.320
4.0 to 4.5	0.300	0.520
4.5 to 5.0	0.530	0.690
5.0 to 5.5	0.730	0.820
5.5 to 6.0	0.860	0.900
6.0 to 6.5	0.940	0.950

LEFT-TURN DECISION PROBABILITY (cont'd)

Lag or Gap Size (sec)	Probability of Accepting Lag	Probability of Accepting Gap
6.5 to 7.0	0.970	0.970
7.0 to 7.5	0.990	0.986
7.5 to 8.0	0.996	0.993
8.0 to 8.5	0.999	0.997
8.5 to 9.0	1.000	0.998
9.0 to 9.5	1.000	0.999
9.5 to 10.0	1.000	1.000

Table A-2.2

spacing condition is considered a lag. If the lag is rejected the driver is required to slow down and stop at the conflict point and thereafter consider gaps in the coming traffic.

LANE CHANGE DECISION PROBABILITY

Lane Change Lag (Sec)	Probability of Acceptance
0 to 0.5	0
0.5 to 1.0	0
1.0 to 1.5	0
1.5 to 2.0	0
2.0 to 2.5	0.090
2.5 to 3.0	0.180
3.0 to 3.5	0.310
3.5 to 4.0	0.490
4.0 to 4.5	0.660
4.5 to 5.0	0.810
5.0 to 5.5	0.900
5.5 to 6.0	0.960
6.0 to 6.5	0.985
6.5 to 7.0	0.995
7.0 to 7.5	0.999
7.5 to 8.0	0.999
8.0 to 8.5	1.000
8.5 to 9.0	1.000
9.0 to 9.5	1.000
9.5 to 10.0	1.000

Table A-2.3

The previous perspective of lag still holds. Only vehicles which stop in a queue become potential lane changers. In lane change conditions, the potential changer first checks to see if a vehicle in the adjacent right lane is already located in the zone into which he must move. In the absence of such conflict the potential lane changer determines the expected travel time to the conflict zone of the next vehicle in the adjacent lane, based on its current position and velocity. This travel time is defined as the lane change lag. The decision to change or not to change is then made probabilistically by reference to the above table.

A-3 Regression Equations

Using simulation, the Gerlough study team performed regression analysis to relate mean system delay to the following secondary measures of performance: (1) mean stopped delay, (2) mean stopped delay per vehicle, (3) mean queue length for the combined intersection approaches, (4) mean delay in queue, and (5) proportion of vehicles stopped. In order to validate the equations the same analysis was performed on data from a different intersection configuration. The results are summarized in the following table.

SUMMARY OF REGRESSION ANALYSES RELATING VARIOUS MEASURES OF PERFORMANCE

Independent Variable	Dependent Variable	Regression Equation	Correl. Coeff.	Standard Error of Estimate	Regression Model Validated
X_1	Y_1	$\tilde{Y}_1=0.1087+1.311X_1$	0.998	0.0144	Yes
X_2	Y_1	$\tilde{Y}_1=0.0491+1.190X_2$	0.998	0.0170	Not Checked
X_3	Y_1	$\tilde{Y}_1=0.0995+0.901X_3$	0.998	0.0175	Yes
X_4	Y_1	$\tilde{Y}_1=0.1700+0.017X_4$	0.996	0.0230	Yes
X_7	Y_1	$\tilde{Y}_1=\dfrac{X_7}{8.11-8.43\ X_7}$	0.960	-	No
X_2	Y_2	$\tilde{Y}_2=0.511+7.703Y_1$	0.970	0.535	No
X_5	Y_2	$\tilde{Y}_2=0.182+1.124X_5$	0.997	0.169	Yes
X_6	Y_2	$\tilde{Y}_2=\ 0.039+0.098X_6$	0.959	0.620	No

NOTES: Y_1= Mean system delay, minutes; Y_2=Maximum individual system delay, minutes; X_1=Mean stopped delay, minutes; X_2=Mean stopped delay per stopped vehicle, minutes; X_3=Mean delay in queue, minutes; X_4=Mean queue length around the intersection, vehicles; X_5=Maximum individual stopped delay, minutes; X_6=Maximum queue length around the intersection, vehicles; X_7=Proportion of vehicles required to stop.

Table A-3.1

APPENDIX B

B-1 Relative Speed-Density Function

The speed-density function employed in the macroscopic simulation of Sakai and Nagoa is simply a one dimensional version of the general equation of state of the traffic stream developed in Appendix A. This relationship represents the association between velocity and concentration and is of the following form.

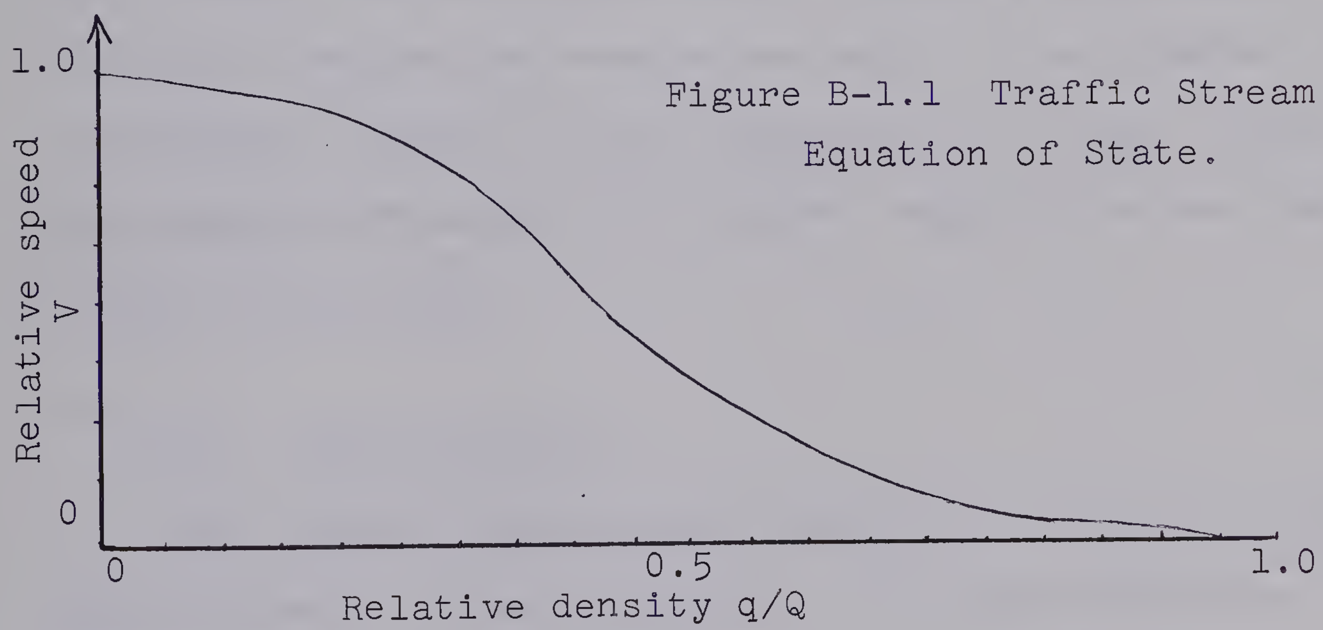


Figure B-1.1 Traffic Stream Equation of State.

It should be remembered here that q is the number of vehicles within a given road segment whereas Q is the maximum number of vehicles this segment could accommodate.

This macro simulation will fail miserably where the geometry of the network does not correspond to the above relative density function. This function of course can be altered to meet real requirements if necessary but Sakai and Nagoa suggest that general function of the above form is satisfactory for most situations.

APPENDIX C

C-1 Program Organization and Logic

The general purpose intersection package can be described as consisting of three parts. These parts can be referred to as (1) Initialization, (2) Simulation and (3) Termination. The initialization part of the program sets up the physical system configuration desired by the user. The simulation part does the actual simulation of the traffic flow through the intersection and records the desired statistics, while the termination part of the program stores intermediate results of the simulation for future trials. This appendix describes the program organization and logic of these three parts.

C-1.1 Initialization

The system configuration desired by the user is specified by a set of input parameters. The initialization routines examine these input specifications and modify the general intersection to the specific one desired. First the desired number of lanes in each artery is implemented by setting logic gates which suppress vehicle generations for the extra inner lanes if all four are not required. Only the inner two of the possible four lanes in each direction have this feature so that each artery always has at least a left and a right turn lane. All user times specified are auto-

matically converted to clock units according to the input ratio specified. This conversion is done prior to any simulation in order to avoid unnecessary recomputation. Finally standard variables are evaluated, according to the system configuration, and stored in common areas so that each transaction does not compute these redundantly. All phases of the initialization procedure are done in the first simulator clock instant so that this initialization does not in any way, effect the simulated vehicle flow.

C-1.2 Simulation

The actual simulation phase of the program concurrently accounts for four parallel processes. These processes are: vehicle flow through the physical system, statistical evaluation of vehicle flow, control of vehicle flow by the simulated phasing scheme, and the implementation of platoon and random arrival rates in cyclic fashion. The following sections discuss these processes in detail.

Vehicle Flow

In describing the logic of vehicle flow, it is convenient to consider only one lane of traffic. In doing this, it shall be assumed that this single lane is used by both left and right turners and non-turners in the real situation. The following flow chart is a detailed description of this single lane logic. Portions of the flow chart appear redundant but are in fact necessary for both peak and non-peak

traffic considerations.

Vehicle Generation

General Purpose Simulation System/360 provides a "generate" block which activates transactions according to any specified mean and inter-arrival rate. The inter-arrival distribution is specified within the program coding, but can be altered to any desired distribution by anyone familiar with G.P.S.S./360. The mean is a variable which must be specified by input to the program. When a mean is specified, the internally coded distribution is effectively scaled by this factor. The current arrival distribution in this package is a negative exponential inter-arrival distribution with a mean of one. The users mean time inputs are used to scale this distribution to produce random individual lane distributions. The platoon inter-arrival headway directly determines the time between successive transaction (vehicle) generations. All generations occur at the user specified system boundary.

Intersection Approach

Before proceeding, the intersection approach philosophy should be well understood. In this area all vehicles are assumed to be free flowing and movement from the system boundary to the stop-line is accounted for on this basis. If on completion of this movement no queue exists, the vehicles still proceed as free flowing. Otherwise the vehicles enter the queue, where driver peculiarities are

assumed to become obscure, and proceed with a constant headway and a common velocity. Both processes are of course subject to signal control. This bimodal treatment successfully represents the motion of both free flowing and queued vehicles and at the same time avoids the extreme complexity of simulating the stimulus-response dynamics of real queue build-up and discharge.

Since the system boundary is to exceed maximum queue length, all vehicles are assumed to be free flowing upon generation. Each vehicle is therefore immediately tagged with a free flow velocity which is also considered to be the vehicle's target velocity in delay calculations.

Vehicles are randomly tagged with a free flow velocity according to a normal distribution from .75M to 1.25M where M is the mean arrival velocity specified for the particular artery. This velocity is maintained until the vehicle encounters some more restrictive condition where it will be reassigned according to the circumstances that prevail. A copy of this free flow velocity is always maintained by each vehicle to be used in the calculation of system delay.

After being tagged with a free flow velocity, each vehicle is delayed by the minimum time required to reach the intersection stop line. This delay is calculated according to the free flow velocity of the vehicle, the distance from the system boundary to the stop line and the turn status of the vehicle. Turning vehicles are required to slow to the

respective maximum turn velocity, and this extra delay is calculated according to the difference between free flow velocity and turn velocity, and the user specified rate of deceleration. These approach delays are uniquely calculated for each vehicle and implemented by the use of the G.P.S.S./360 "advance" command. This block suspends a transaction until its calculated delay is complete whereupon the transaction continues to the next logic block. The advance block is capable of servicing many transactions simultaneously and since the delay time is calculated with respect to a common distance and a particular velocity, vehicles may implicitly pass within the delay process. Thus the sequence of arrivals at the intersection may be completely different from that of the vehicles at the system boundary. Since real passing is not evident in the vicinity of the intersection, the simulator overrides the apparent passing in the delay function by using an indexing filter to preserve the arrival sequence. Prior to encountering the minimum approach delay, vehicles are sequentially indexed in parameter three. After the minimum delay a testing function allows the vehicle to proceed only in the correct sequence. In this way the blocking condition of the filter effectively simulates follower behavior during the intersection approach.

In order to sustain follower behavior within the intersection the following procedure is employed. When a vehicle emerges from the filter, it is determined whether or not this

vehicle has been impeded. If motion was restricted and the previous vehicle was not a turner, the limiting velocity is attributed to this vehicle. If motion was not impeded or the preceeding vehicle was a turner, no velocity redefinition is encountered. The velocity redefinition is omitted for restricted vehicles following turners because the real turner restriction is not sustained throughout the intersection.

Referring to the flow charts, it can be noticed that the minimal approach delay is effected in three stages. The first delay is the time required for a vehicle to travel from the system boundary to the beginning of the left turn conflict zone of the opposing flow. The second delay is the time required for the vehicle to pass from the beginning of the first conflict zone to the entry point of the second. The second conflict zone is defined relative to right turners of the adjacent right hand artery (see diagram 3.2). At the end of each delay the vehicle is noted to have entered the respective conflict zone by entry into a G.P.S.S./360 "storage". The final stage of the minimal delay is the time required for the vehicle to pass from the entry point of the second conflict zone to the intersection stop line. It is at this point that vehicles are probabilistically tagged as turners according to the user specified percentage of turners, and subjected to the extra "slow down" delay. The vehicle now enters the queue and proceeds according to

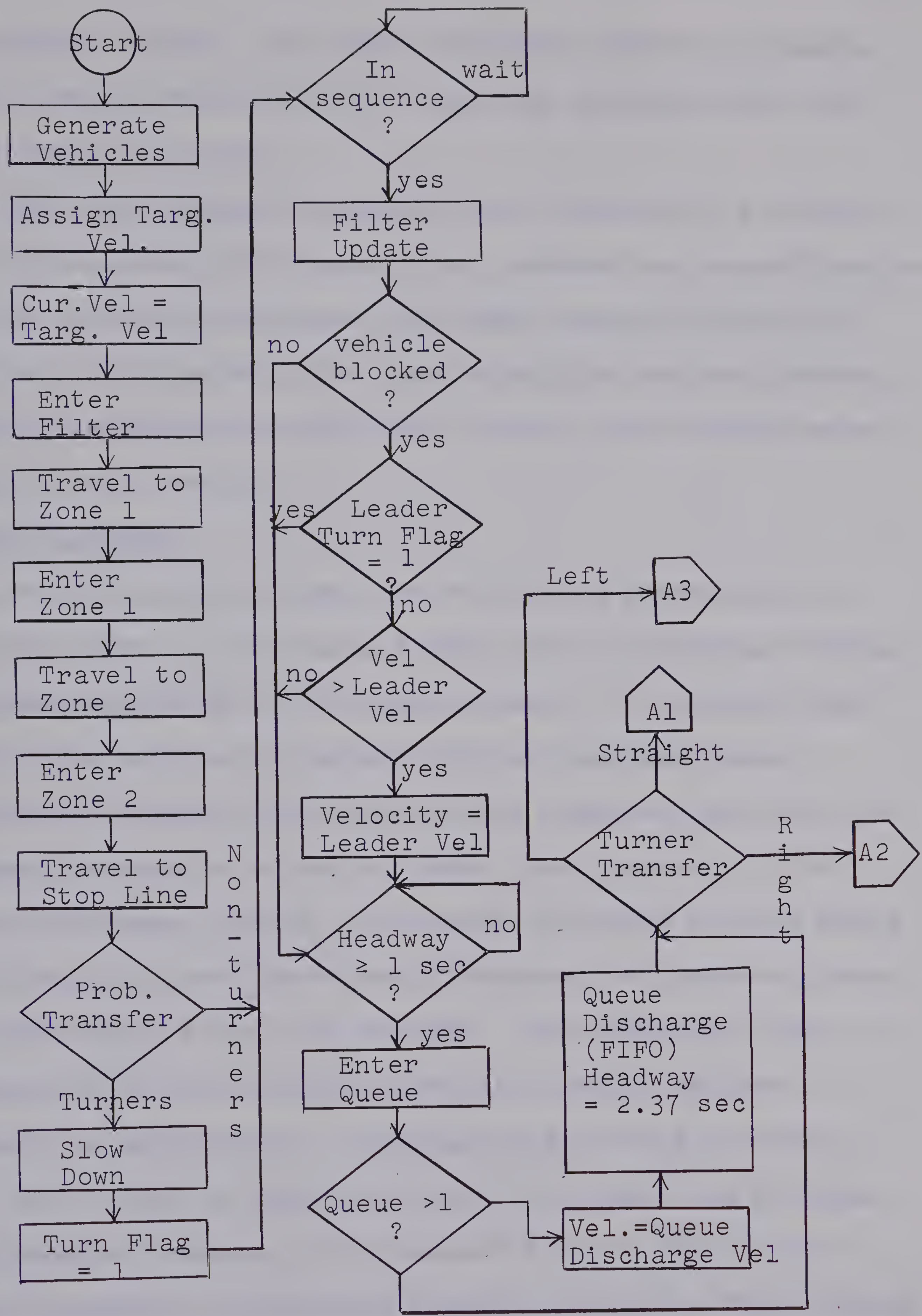


Figure C-1.2.1 Vehicle Flow - Intersection Approach

the signal status. The queue discharge function preempts free flowing behavior if the queue now contains more than the current vehicle.

The above delays encountered are dynamically evaluated by the simulator with respect to: geometrical specifications of the intersection system, the mean approach velocity of the particular artery, the turn velocities and the general rate of deceleration specified, and the free flowing velocity of each vehicle.

Queue Discharge

At this point in time, the vehicle is potentially at the stop line. If no queue exists the free flowing vehicle proceeds according to the signal status. If a queue does exist, the vehicle is tagged with the constant queue discharge velocity, specified by the engineer, and the subsequent resumption of motion comes under control of the queue discharge process. The queue discharge process keeps vehicles in correct order and disperses the queue at a rate of one vehicle every 2.37 seconds. This discharge rate is suppressed by any blocking condition such as delayed turners or pedestrians. Although free flowing vehicles (ie. not queued at this point) are not restricted by queue discharge procedures, it is assumed that at least a one second headway is maintained between successive free flowing vehicles. These constant headways are invoked by a gating procedure based on the G.P.S.S./360 clock which is readily

accessible. Turning vehicles are also dispersed from queue in the above fashion but the velocity attributed to all turners is the user specified turn velocity.

<u>Intersection Passage</u>

Upon becoming the first vehicle in queue, the vehicle transaction is routed to left, right or straight through routines according to its turn status. All turning vehicles are immediately removed from their respective conflict zones, whether or not the signal allows them to proceed. Turn intentions should now be evident. This is particularly true for exclusive left and right turn lanes. The vehicle is now under the control of the signal scheme and the transaction encounters a series of tests to determine the signal status and react accordingly. It becomes convenient here to consider the turn and non-turn procedures separately.*

<u>Non-Turns</u>

The through vehicle departs from queue immediately if the signal is green, or if the signal is amber and the decision is made to run the amber. The amber decision routine is a probabilistic function based on the deceleration required to stop when the light changed to amber (see Table 3.4.5.1 for actual probabilities of stopping). Otherwise the vehicle transaction waits within the signal check routine until the signal goes green. Note that the waiting vehicle has not departed from queue and it remains first in line at the intersection. If the through vehicle has been waiting

*See Figures C-1.2.2, C-1.2.3, and C-1.2.5

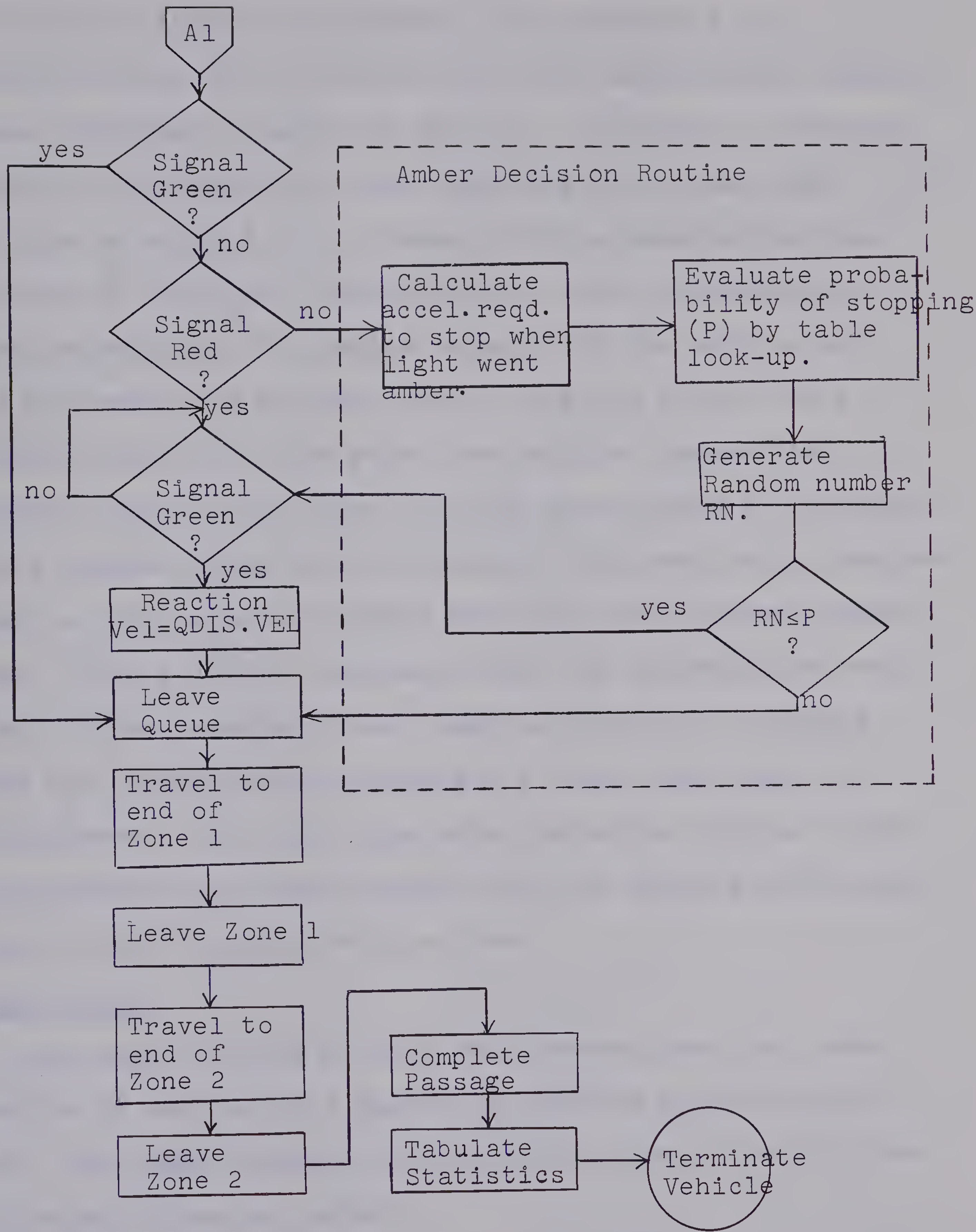


Figure C-1.2.2 Intersection Passage - Non-Turners

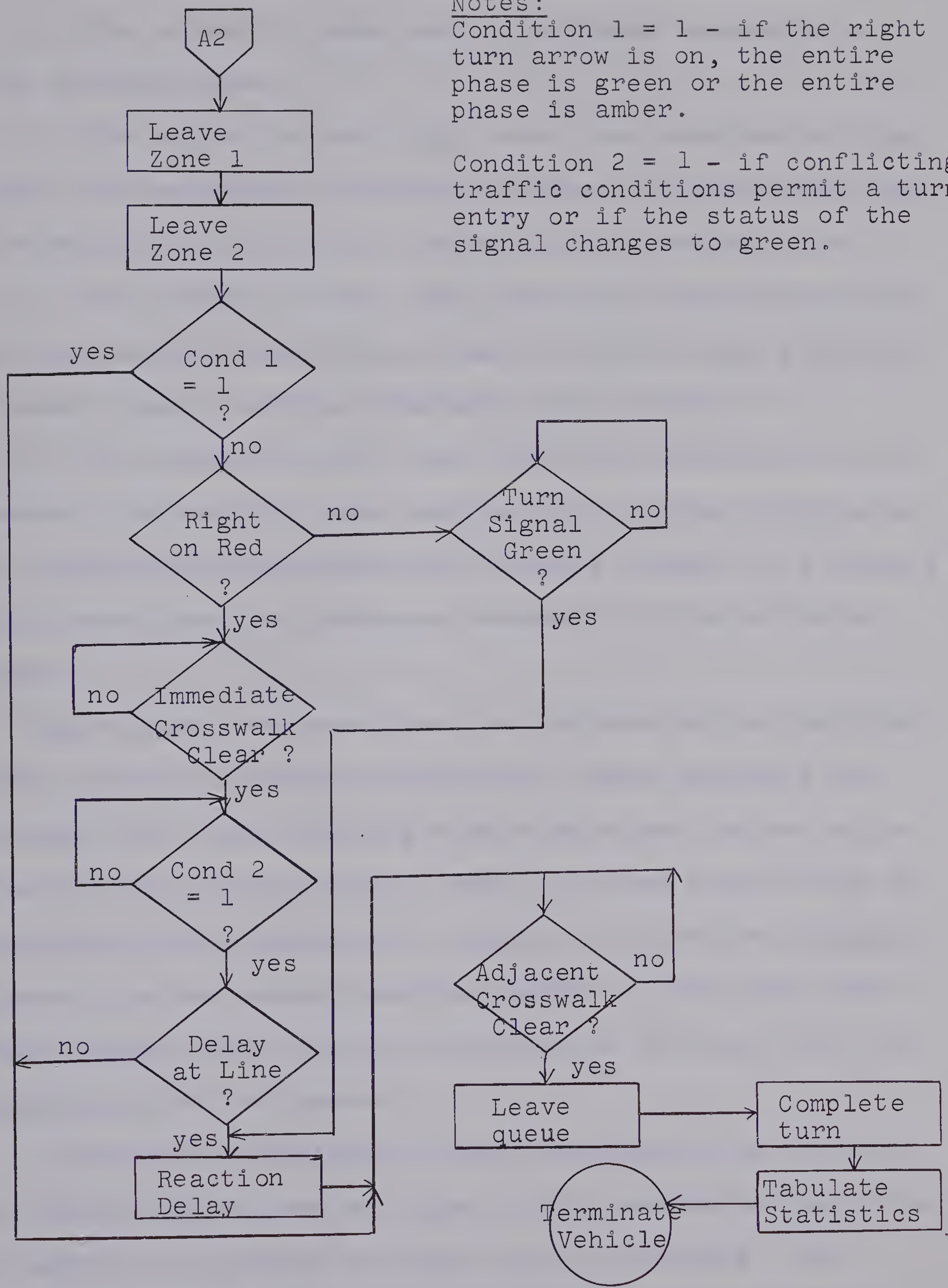
at the stop line for the green, it is subjected to a reaction delay of one second before the hypothesized constant queue discharge velocity is assumed. Otherwise no reaction factor is encountered. Upon departing from queue, the vehicle is delayed by the amount of time required to reach the end of the first conflict zone. This calculation is made according to the tagged velocity of the vehicle and the distance from the stop line to the end of the first conflict zone. At this point the vehicle (transaction) is removed from the left turn conflict zone (variable "storage") and a further delay is encountered. This next delay provides time for the vehicle to reach the end of the second conflict zone. This point is concurrent with the intersection entry line for the opposing flow. Here the vehicle is removed from the second conflict zone and a final time delay is encountered. This last time delay moves the vehicle to the intersection discharge boundary which is defined as the stop line for the oncoming vehicle flow.

<u>Right Turns</u>

The right turning vehicle will proceed into the intersection if any one of a number of required conditions are met. The right turner will depart from queue if any of the following situations occur:

1. The signal is green and the adjacent (turn) crosswalk is free of pedestrians.

2. The right turn arrow is on.



Notes:
Condition 1 = 1 - if the right turn arrow is on, the entire phase is green or the entire phase is amber.

Condition 2 = 1 - if conflicting traffic conditions permit a turn entry or if the status of the signal changes to green.

Figure C-1.2.3 Intersection Passage - Right Turners

3. The signal is amber and the adjacent crosswalk is free of pedestrians.

4. The signal is red, right turns are permitted on a red light, the immediately crosswalk is clear of pedestrians and an acceptable gap exists in the conflicting vehicle flow.

5. The signal is red, right turns are permitted on red and the possibly conflicting lanes of traffic face a red or an amber signal, and the immediate walk is clear.

6. The signal is red, right turns are permitted on red signals, the conflict zone contains only turning vehicles or the conflict zone contains only vehicles blocked by a delayed left turner, and the immediate crosswalk is free of pedestrians.

These right turn conditions are implemented in the signal check routines by boolean variables. These variables are arranged such that a waiting turner appraises the new situation at every state change. When a waiting turner finds an acceptable turn condition the resumption of motion is again delayed by a one second reaction factor. If the turn condition exists when the vehicle arrives at the turn area the reaction factor is bypassed.

It should be noted that if turn condition 1 or 2 is met, the vehicle exits from the signal check routine and waits for the adjacent crosswalk to clear before proceeding. The vehicle, although definitely beyond the influence of the signal, is not yet deemed to have departed from the queue.

This queue departure will not be recognized until the pedestrian clearance check is satisfied whereupon the normal turn transit time is invoked. Since in the real situation such vehicles do not require the whole of the normal passage time to complete the turn, the usual reaction delay is hereby omitted. This effectively accounts for about one-half of the normal turn time which is realistic. Vehicles which are required to wait for the immediate crosswalk clearance are subject to the reaction factor and subsequent motion is still controlled by signal status and vehicular conditions.

Upon departing from queue, the right turner is effectively delayed by the time required to complete the turn. This time is a function of the user specified turn velocity and turn length. Turn times are evaluated from stop line to stop line which is the required input turn length.

Vehicles which proceed straight through the intersection in an outside (right turn) lane are treated exactly the same as regular non-turners. These vehicles are effectively blocked by preceeding right turners until the turner departs from the queue.

Left Turns

Left turns are accomplished in three stages. These three stages are identifiable with the following diagram where:

- the heavy dotted line denotes the path of a left turner from artery 3;

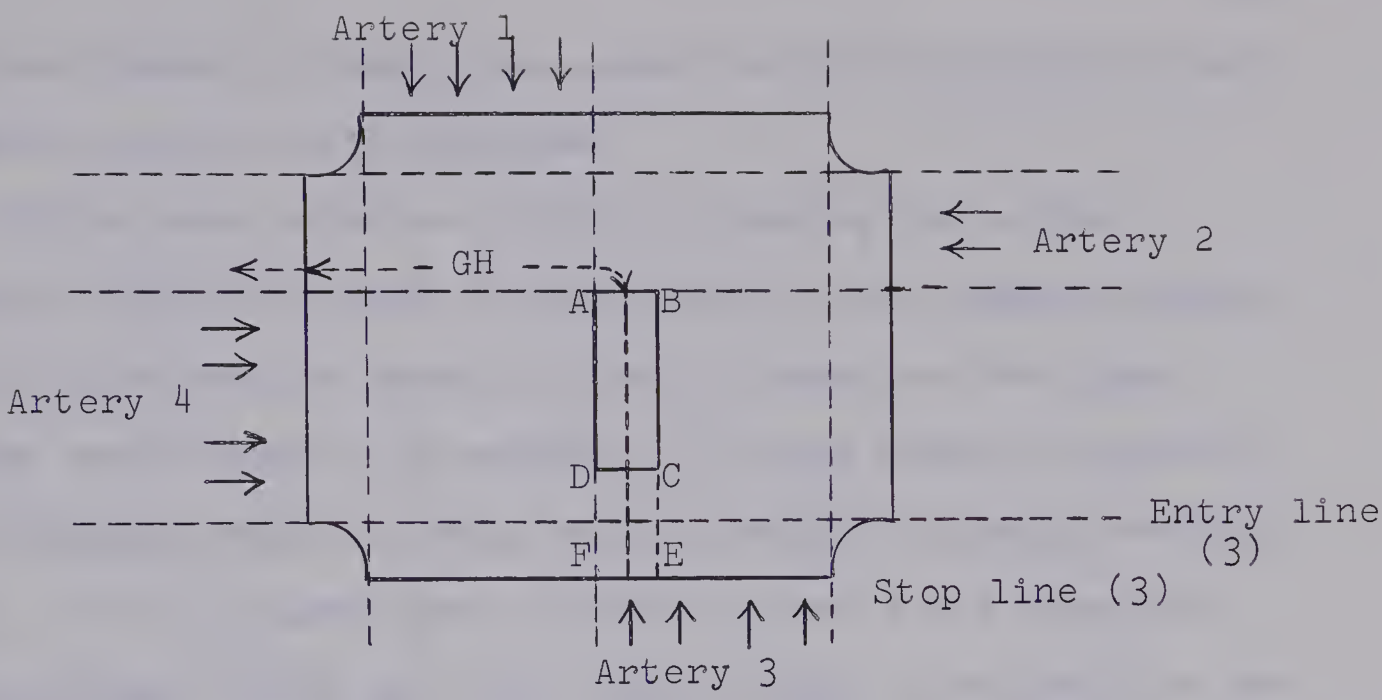


Figure C-1.2.4 Left Turn Movements

- ABCD denotes the left turn junction cell (the length of this cell is specified by the user as the effective length of a queued vehicle);
- DCEF denotes the approach to the intersection junction cell;
- GH denotes the distance from the junction cell to the turn completion boundary.

The position of the junction cell within the intersection is set up at system initialization time according to the system input configuration specifications. The junction cell is positioned right at the point of conflicting traffic according to the number of lanes specified in each direction. The calculation of the approach distance is based on the distance from the junction cell to the appropriate stop line. The remainder of the turn distance (GH) is calculated as the difference between the user specified length of turn

and the distance already accounted for by the junction cell and the junction cell approach.

Inside lane vehicles, prior to testing the signal status, test the status of the junction cell approach area and if this area is empty or free of vehicles the signal status check routine is entered. If this area is occupied by a vehicle, the following vehicle waits till this area is free. It is assumed that the junction cell and junction cell approach areas are only large enough to accommodate one vehicle each. They are therefore defined as G.P.S.S./360 "facilities". When the leading vehicle finds the approach area free it immediately assumes occupancy of this facility and proceeds according to the signal status. If the signal is green or if the signal is amber and the driver has decided to run the amber, the vehicle transaction encounters a delay sufficient to move the vehicle from the stop line to the beginning of the left turn junction cell. Note that if the vehicle has been delayed, by either signal status or by a blocking vehicle, the usual reaction factor is encountered. The approach area passage time is calculated according to the length of the approach area and the mean speed of left turners specified by the user. The vehicle is now in a position to occupy the left turn junction cell. Once again the status of the desired facility (junction cell) is tested. If it is free the junction cell approach area is released for any subsequent vehicles and the vehicle

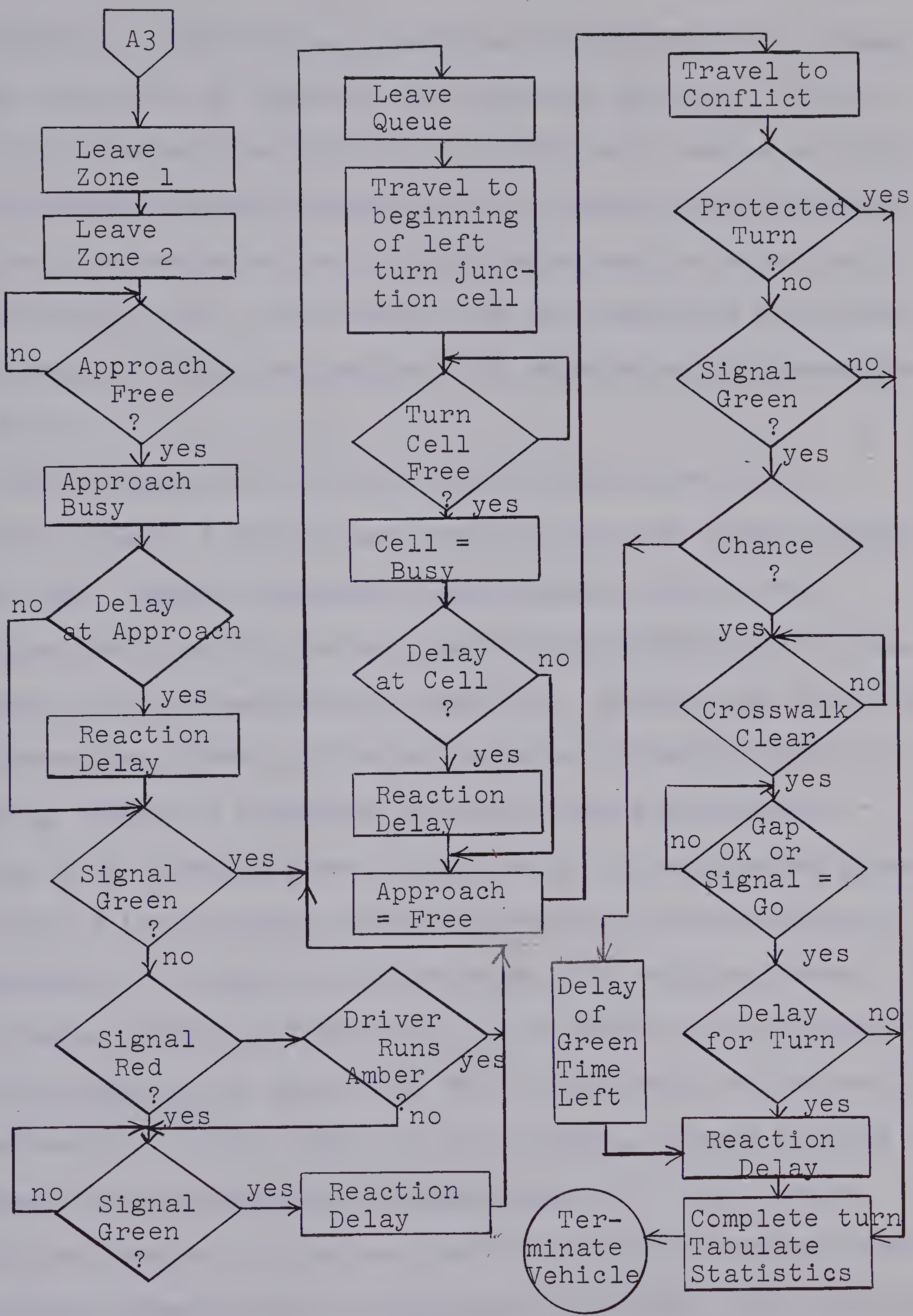


Figure C-1.2.5 Intersection Passage - Left Turners

undergoes the junction cell passage time delay which brings it to the point of conflict for opposing vehicles. If the cell is occupied the vehicle is blocked and remains so until the blocking vehicle beings to move, whereupon the reaction factor is encountered and the following vehicle moves into the junction cell. The vehicle has now completed the first two stages of left turn motion. It remains only to complete the turn.

Turn completion, if turns are not protected or on a separate phase, involves gap analysis at every state change. Since left turners encounter substantial conflict from opposing vehicles the boolean variable implementation of gap analysis is not economically feasible. Instead the following treatment is offered. Turning vehicles initially test the phasing scheme to determine if left turns are protected - either by a flashing green signal or by a free flowing phase. If such is the case the vehicles complete the turn without hesitation. If such is not the case, the vehicle checks the signal status to determine if the light is still green. If the light is not green the vehicle proceeds in the turn immediately. If the light is still green, a check is made against the user specified "chance option". This option specifies whether or not real left turns can be accomplished during the green phase of the signal. In most peak situations there is no chance. If no chance is specified, the gap analysis feature is bypassed and the transaction is scheduled

to proceed in the turn one second after the signal changes - to amber or to a flashing green. This treatment successfully avoids the evaluation of a seven component boolean variable at every state change in favor of a single computation. If the chance indicator is specified as allowing left turns during the green phase, the vehicle transaction proceeds to pedestrian and gap analysis. Pending an acceptable gap or a signal change, the vehicle completes the turn. The final turn delay takes the vehicle to the appropriate discharge boundary at the specified turn velocity.

Straight through vehicles, in left turn lanes, are handled in the same stages as above except that the non-turning vehicle does not "occupy" the left turn junction cell. At this point there can be no blocking condition for non-turners and the vehicles proceed as in the straight through routines. Straight through vehicles do however occupy left turn junction cell approach areas where they may be blocked by any delayed left turner. In this way further queue discharge is suppressed and the real blocking condition is effectively simulated.

Pedestrian Delays

The crosswalk clearance check for pedestrians involves a comparison of the current simulator clock time and the time at which the particular walk was scheduled to have been cleared. The time for clearance is specified by the user and immediately follows the walk signal. The walk signal is

synchronized with the steady green of the adjacent input artery.) The scheduled time for clearance of a given walk is then the clock time at which the corresponding signal went green plus the duration of pedestrian activity specified. In this way it is possible for the user to have the crosswalk effectively occupied for longer than the pedestrian signals allow. This behavior is often evident in downtown areas. In all cases pedestrians have the right of way.

Statistical Evaluation of Vehicle Flow

Statistics gathered in the model are derived from a basic G.P.S.S./360 feature - a transit time indicator uniquely associated with each transaction. This indicator is set to the clock time at which the transaction was generated and its value is not altered throughout the program. When a vehicle completes intersection passage, the difference between the current clock time and the generation time is calculated. This is the transit time in the system in clock units. This value is tabulated in a frequency table and is available as output for each of the four arteries. The measure in itself is an indicator of system efficiency and is used in the validation process. This simulated transit time also provides the basis for vehicle delay calculations. The equation used for the calculation of delay is:

Delay = Actual transit time - desired transit time;

where the desired transit time is calculated according to

vehicle routing and target velocity. Slow down time is considered as necessary for free flow turners and this time is again accounted for by the user specified rate of deceleration. The delay time output also contains a frequency table and statistics.

Phasing Schemes

The phasing schemes included in the model are each self-contained perpetual loops with only one entry point. At initialization a dummy transaction is created which is directed to the correct phasing loop by the user specification of desired scheme. The scheme then begins at simulator clock time one and continues without interrupt until the simulation run ends. The logic of each scheme is simply the setting and resetting of logic switches and assigning values to signal variables. Each artery is controlled by a single variable which takes on the values 1, 2, and 3 to denote green, amber and red lights respectively. The successive assignments of 1, 2, and 3 to a particular signal are separated by the user specified green and amber times respectively. These times are implemented by the action of the G.P.S.S./360 advance block on the dummy transaction. Note that if no time is specified for a particular phase, the simulator does not treat this as an error; the phasing scheme will be implemented with the missing specification equal to zero. The setting and resetting of logic switches, denotes free flow and conflicting

flow respectively, for a particular phase. In this way protected left turns are accomplished by turning the appropriate signal green, setting the appropriate free flow indicator (logic switch), and delaying the dummy transaction by the user specified flashing green time. The logic switch is then reset and the steady green continues. The amber signal between any two phases is constant but the value of the constant is under user control.

Platoon and Random Inter-arrival Rates

Platoon behavior, if specified, will be implemented in a cyclic fashion for each of the arteries. The control routine which initiates platoon and random behavior is a parallel routine accounting for up to sixteen loops concurrently. Each loop is driven by a single transaction and the logic of each of these loops is exactly as follows.

1. Activate platoon arrival rate.
2. Advance user specified platoon duration time.
3. Deactivate platoon arrival rate.
4. Advance (platoon period - time specification 2).
5. Transfer back to 1.

For a given artery with platoon behavior, four loops operate in phase such that all four dummy transactions are at step 1 of their respective loop simultaneously. The duration of each platoon in each lane is completely controllable and may even be set to zero.

At initialization time these dummy transactions are

created by duplicating the initializing transaction sixteen times - or as many times as necessary for the specified behavior. These duplications occur in two stages and are accomplished by means of the G.P.S.S./360 "split" block. Upon examining the user specification for platoon behavior the main initializing transaction creates a copy transaction (via the split block) for every artery exhibiting platoon behavior. These dummies are then routed to the required arterial platoon routines - PLAT1, PLAT2, PLAT3, or PLAT4 where they are further subdivided. Upon receiving a dummy transaction the platoon routine delays this dummy transaction by the offset specified for the given platoon arrival at the system boundary. The platoon routine then makes three more copies of the dummy transaction and routes these to each of the above explained lane routines. Since each platoon routine received the dummy transaction at clock time 1, this initial offset controls the phasing of the arterial platoons with respect to each other and with respect to the phasing scheme.

The activation of platoon arrival rates, while at the same time sustaining random arrival rates, is accomplished by providing each lane in the model with two vehicle generators. One generator is driven by a user specified mean inter-arrival rate and an exponential distribution with a mean of one. This distribution is stored within the main program but can be readily altered by replacing a few cards.

The second generator is driven only by the user specified mean inter-arrival time and produces regular arrivals at this rate. Both generation rates can be indefinitely suppressed by any blocking condition. This capability is directly used in invoking mixed arrival rates. A blocking condition in G.P.S.S./360 occurs when the requirements of the following operational block are not satisfied by the transaction attempting entry. Thus unconditional tests of the following nature are imposed on the vehicle generators in order to produce mixed arrival rates.

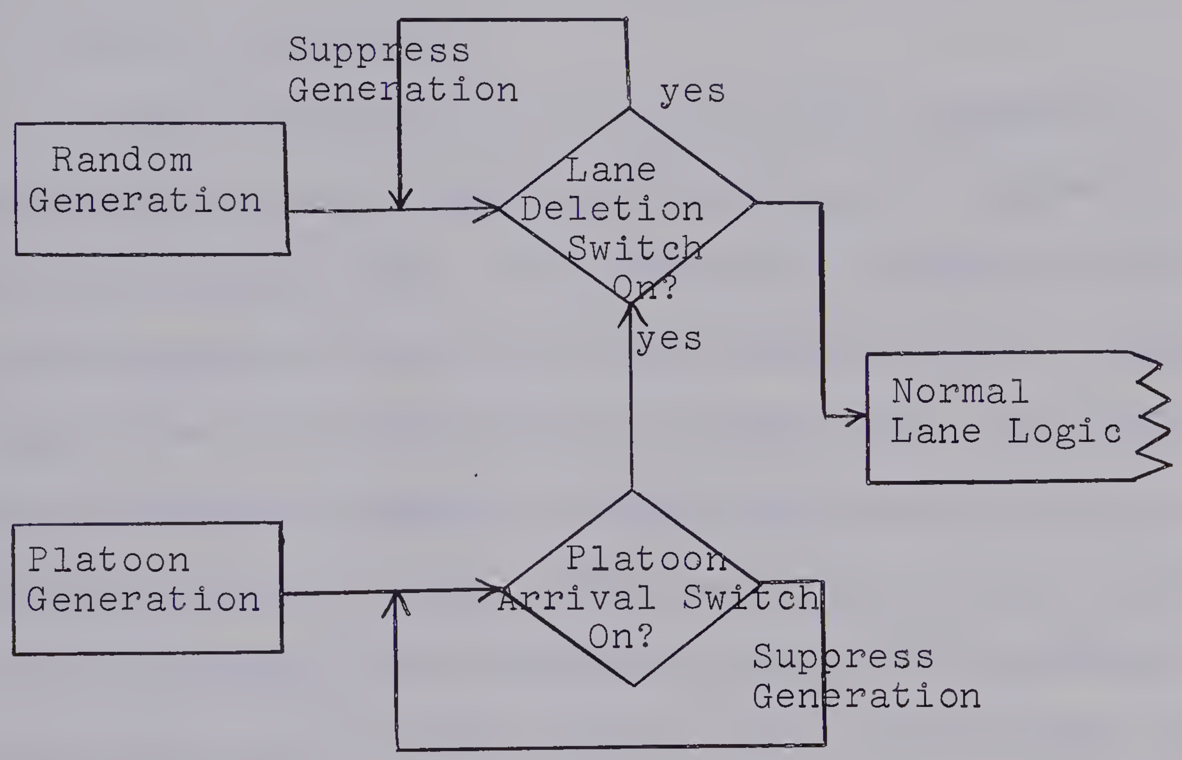


Figure C-1.2.6 Mixed Arrival Logic

This type of superimposed arrival distribution allows some random variation over and above the constant platoon arrivals specified. These variations must be accurately anticipated

by the user and accounted for in the input specifications. The mixed arrival rates are implemented by the parallel timing routines which only set and reset the controlling logic switches in accordance with the user specified platoon characteristics. In the inner lanes of the model these logical gates are expanded to boolean variables so that complete lane deletion suppresses both generators. Lane deletion switches are set at initialization time as described previously.

C-1.3 Termination

The termination of a G.P.S.S./360 program is accomplished by the complete processing of a number of specified transactions. This feature is somewhat modified in the simulator so that the user can specify the length of real time to be simulated in a given run. This modification involves a separate timing loop which refers to a termination count of one. When the real time to be simulated has been surpassed the termination count is decremented to zero and the G.P.S.S./360 monitor halts processing. The simulator also includes the "SAVE" feature provided by G.P.S.S./360 which allows the user to retain the current state of the model, on tape, and to resume simulation from this point at some later time.

C-2 Input Variables for the Simulator

All input variables must be specified or they will be automatically set to zero. In most cases specification errors will produce G.P.S.S./360 execution errors and system diagnostics will result. However, in some cases specification errors will not show up in the listing and the result will be biased results. Since no error checking conditions are included in the intersection package, correct specification is the user's responsibility. The following variables may be specified. (Distance parameters are in feet and time parameters in seconds).

XH1-XH4 denote the number of lanes in arteries one to four respectively. When specifying less than four lanes the user must remember which lanes will be deleted. For example, the specification XH1=2 will delete lanes 2 and 3 whereas the specification XH1=3 will delete only lane 2. The indexes of the other lanes do not change. The deletion procedures in other arteries are exactly the same except for the lane numbering.

XH5 specifies the north-south width of the intersection from entry line to entry line.

XH6 represents the east-west length of the intersection from entry line to entry line.

XH7 is the distance from each stop line to the system boundary.

XH8 is the length of each of the left turn junction cells

in the model. This can usually be taken to be the effective length of a queued vehicle.

XH9 specifies the number of simulator clock units representing one second real time. Since all calculations are integral, this specification can help to overcome truncation.

XH10 is the phasing scheme choice indicator. This may be specified as having the values 0 to 10. Remembering that the southbound, westbound, northbound, and eastbound arteries are referred to as arteries 1, 2, 3 and 4 respectively, the following table denotes the relationship between the indicator value and the phasing scheme.

PHASING SCHEMES

Indicator Value	Phasing Cycle
0	2 way: (1+3),(2+4)
1	3 way (1+3),2,4
2	3 way (1+3),4,2
3	3 way 1,3,(2+4)
4	3 way 1,(2+4),3
5	4 way 1,2,3,4
6	4 way 1,2,4,3
7	4 way 1,3,2,4
8	4 way 1,3,4,2
9	4 way 1,4,2,3
10	4 way 1,4,3,2

Table C-2.1

Note that all phasing schemes with opposing flows have the extended option of either leading or lagging flashing greens. To incorporate the protected turns the user only needs to specify the duration of the desired flashing green.

XH11-XH22 are right turn arrow options. By specifying these options as ON (ie. one) the user can designate which right turn arrow is ON concurrently with some other phase. For example XH11-XH13 refer to artery one. If XH11 is set to one, right turners from artery 1 will proceed freely whenever the signal for artery 2 is green. If XH12 is set to one the same right turners will proceed whenever artery 3 has the green light and finally if XH13 is one, the turners will proceed when signal four is green. These green arrows, if specified as 1, will be ON for the duration of any steady or flashing green or both of the designated artery and there is no provision for "flashing green only" arrows. The case of the right turn arrow of artery 1 being ON while artery 2 is green is very uncommon but is included for the sake of completeness and for ease in interpretation. XH14-XH16, XH17-XH19, XH20-XH22 refer to arters 2,3, and 4 respectively and each variable corresponds to the next artery in clockwise fashion.

XH23-XH26 denotes the lengths of right turns for arteries 1 to 4 respectively. These turn lengths must be specified from stop line to stop line.

XH27-XH30 are the mean right turn velocities for each of

the above right turns in feet per second.

XH31-XH34 specify the percentage of turning vehicles for right turn lanes in arteries 1 to 4. This percentage must be expressed as the number of turners per one thousand arrivals. For example if twenty-five percent of the arrivals in lane 1 actually turn, the specification for XH31 must be two hundred and fifty.

XH35-XH38 are the lengths of left turns, in feet, for arteries 1 to 4 respectively. Again these turn lengths must be specified from stop line to stop line. (All left turning vehicles follow the same path).

XH39-XH42 specify the mean velocities, in feet per second, for the above left turns. Again the relationship is respective.

XH43-XH46 are the number of turners per one thousand arrivals in the corresponding left turn lanes. The type of specification required is the same as that previously described for the right turners.

XH47 is the constant queue discharge velocity to be attributed to all non-turning queued vehicles. This specification is in feet per second.

XH48 is the right on red indicator. If this variable is not specified, or is specified as zero, the simulator assumes that right turns are permitted on red lights for all approaches. If the variable is not set to zero, right turns will not be permitted on red lights.

XH49-XH64 are the vehicle mean inter-arrival times for lanes 1 to 16 respectively. These means shall be used only with the random arrival rate. The specification is in seconds.

XH65-XH68 are the leading flashing green times for arteries 1 to 4. Phasing schemes which do not allow flashing greens for certain arteries will ignore the specifications that are irrelevant.

XH69-XH72 denote the lagging flashing green times for the corresponding arteries 1 to 4. If a particular artery has been specified with both a leading and a lagging flashing green, the latter will be ignored.

XH73-XH76 represent the main or steady green times for the respective arteries 1 to 4. This specification does not include any leading or lagging flashing green times. If protected left turns are specified they will be in addition to the steady green specified.

XH77 is the amber clearance interval. This specification applies for all directions in the system. Lagging and steady greens are both followed by the same amber phase. This specification may be set to zero in order to avoid execution of the amber decision routine.

XH78-XH81 are the chance indicators for possibly conflicting left turn lanes. If these are not specified, or set to zero, the simulator will not allow left turns during a green phase for possibly conflicting streams of traffic.

The logic of the left turn lane is such that up to two vehicles may be waiting within the intersection during the green and they will proceed with the turn when the signal changes to amber. Any free flowing phase preempts this specification. The same is true of flashing green signals. If left turns do occur during the green phase in the real situation, the respective left turn lane chance indicator should be set to one.

XH83-XH86 provide initial offsets for the platoon arrivals at the system boundary. XH83 denotes the time in seconds from the start of the green for artery 1, or from the leading flashing green of arteries 1 or 3 if their steady phases are operating concurrently, to the time of the first platoon arrival at the system boundary in artery 1. Similarly XH84 denotes the time lapse from the same real reference point to the arrival of the first simulated platoon in artery 2. Subsequent to this initial offset, the platoon timing is maintained by the constant platoon periods specified. If no platoon behavior is specified (platoon durations equal to zero), these specifications will be ignored.

XH91-XH94 express the platoon periods for arteries 1 to 4. If any of these variables are not specified, or set to zero, no platoon behavior will be simulated for these arteries. The platoon period is the constant time between successive platoon arrivals, in a given artery, at the

system boundary.

XH95-XH110 designates the platoon duration times for lanes 1 to 16 respectively. These specifications allow the user considerable flexibility in simulating a variety of arrivals in different lanes of the same artery. These may even be specified as zero for a given lane whereby the arrival rate will always be random.

XH111-XH114 are the times that the crosswalks, blocking arteries 1 to 4 respectively, are effectively occupied. These times go into effect with the appropriate green phase (steady green only) and no vehicles are allowed to cross these walks until after the specified clearance time. These times may exceed the usual pedestrian walk time or even the usual green phase.

XH115-XH118 are the crosswalk widths. These distances are taken to be from the stop line to the entry line of the intersection for each of the respective arteries (1 to 4).

XH119-XH122 are the mean free flow velocities for each of the arteries. These are specified in feet per second and not only determine vehicle entry speed into the system, but are instrumental in initially defining left and right turn conflict zones.

XH124 denotes the real time in minutes to be simulated during this computer run. Usually thirty minutes of real time gives an adequate appraisal of the situation.

XH126 specifies the rate of deceleration to be used by vehicles slowing to turn. This specification is in feet per second.

This completes the input specification requirements. The following section explains the control cards required to use the model and the format of the input specifications.

C-2.1 Sample Input

The following diagram* shows the entire array of control and input cards necessary for a simulation run.

For the cards shown, the run proceeds as follows. The simulation of the specified intersection is started and run for a real time of five minutes. The run is temporarily stopped and all accumulated statistics are set to zero. No print out is available at this point. Once again the run is started and progresses for thirty minutes of real time. Summary statistics are now printed out and the state of the model is saved on the system tape.

The reason that the model is run for five minutes and the accumulated statistics set to zero is to provide the system with a warm up so that the statistics may be gathered on the system while it is in a steady state. Initially the system has no vehicle in it what-so-ever and this is not very realistic for an intersection.

The purposes of the G.P.S.S./360 control cards are as follows:

---

* See Figure C-2.1.1 Sample Input.

CARD FORMAT

Card Columns

```
8          19
REALLOCATE FAC,10,STO,16,QUE,16,LOG,50,TAB,8,FUN,6,FSV,100
REALLOCATE HSV,200,CHA,0,GRP,0,FMS,0,HMS,0,MAC,0
REALLOCATE COM,80000,BLO,2200,BVR,34,VAR,145,XAC,2000
SIMULATE
READ
CLEAR
INITIAL    XH124,5
INITIAL    XH1-XH4,4/XH5,80/XH6,92/XH7,300/XH9,4/XH10,0/XH8,22
INITIAL    XH23-XH26,22/XH27-XH30,10/XH31,940/XH32-XH34,750
INITIAL    XH35,112/XH36,118/XH37-XH38,112/XH39-XH42,24
INITIAL    XH43-XH46,1000/XH47,24/XH49-XH64,10/XH66,10
INITIAL    XH73-XH76,30/XH77,4/XH82,1/XH84,35/XH86,30
INITIAL    XH87-XH90,2/XH91-XH94,73/XH95-XH110,15/XH119-XH122,35
INITIAL    XH115,20/XH116,15/XH117,14/XH118,15/XH126,6
RESET
START      1,NP
INITIAL    XH124,30
START      1
SAVE
END
```

Figure C-2.1.1 Sample Input

REALLOCATE sets up the G.P.S.S./360 system core resources. These cards must be included for every run.

SIMULATE tells the system (G.P.S.S./360) that an execution run is desired.

READ reads the intersection simulation program from tape and puts the model in core at its latest state. By saving the model in an active state, the assembled version of the intersection simulator is available and the lengthy assemble feature can be bypassed. The READ card also reads the subsequent punched card input.

CLEAR is a G.P.S.S./360 control card which destroys all transactions currently active within the model. This card also sets all previously defined variables and the simulator clock to zero. If a continuation run is desired the CLEAR card is omitted. For the continuation run, the model begins in the state at which the last run ended and all variables remain the same as they were previously defined unless they are currently specified. Only those variables initialized in the current deck will be changed from the last run if the CLEAR card is omitted.

INITIAL is the user input card. The format shown in the diagram must be adhered to. If multiple specification (ie. XH1-XH4, sets variables XH1 to XH4 inclusive to four) is desired the following rule must be observed. For any pair of variables specified as XHi-XHj,n, it is imperative that i<j. In general, input specifications cannot extend

into column 72.

START1, NP tells the simulator that all input variables have been received and that the run may commence for as long as was specified by the real time input. The NP option suppresses the print out of summary statistics.

RESET sets all accumulated statistics to zero. The state of the system is not altered and the program remains active and reads the next card. If a warm up is not necessary or undesired the reset card is simply removed.

INITIAL XH124,30. This card redefines the clock variable such that the simulator will run for thirty minutes after reading the rest of the new input.

START1 once again signifies the end of the current input and execution of the simulation model is resumed. The no print option is omitted so that summary statistics will be printed at the end of this run.

SAVE rewrites the model in its current state on the system tape. By saving the model each time a further continuation run is possible. This type of continuation run is imperative where computer time limits are restrictive.

C-2.2 Sample Output

The following figure displays the typical output for a simulation run. It should be remembered that additional output, in the form of frequency tables, is available upon request. This request is made by adding an OUTPUT card to

the input deck - immediately after the START1 card.

```
EFFICIENCY OF SYSTEM SIMULATED
ALL TIMES ARE GIVEN IN SIMULATOR CLOCK UNITS
------------------------------
------------------------------
MEAN SYSTEM DELAY ARTERY 1 = 63.63
MEAN SYSTEM DELAY ARTERY 2 = 72.46
MEAN SYSTEM DELAY ARTERY 3 =106.52
MEAN SYSTEM DELAY ARTERY 4 = 85.63
MEAN TRAVEL TIME ARTERY 1 =112.88
MEAN TRAVEL TIME ARTERY 2 =121.78
MEAN TRAVEL TIME ARTERY 3 =155.16
MEAN TRAVEL TIME ARTERY 4 =139.51
NUMBER OF SOUTHBOUND VEHICLES THRU =154
NUMBER OF WESTBOUND VEHICLES THRU =136
NUMBER OF NORTHBOUND VEHICLES THRU = 78
NUMBER OF EASTBOUND VEHICLES THRU =155
```

Figure C. 2.2.1 Sample Output

Caution is urged in using the simulator. Since G.P.S.S./360 is a non-conversational language no intersection input error checks are included other than the standard G.P.S.S./360 format scan. Thus it is the user's responsibility to specify input in correct format and in reasonable context. For example if the user were to specify an inter-arrival generation rate of zero, all available core would be used up almost instantly.

APPENDIX D

D-1 Data Gathering and Analysis

The purpose of this appendix is to present a brief account of the field work involved in this project.

Initial statistics were gathered during both morning and afternoon peak times at the intersection of 109 Street and 82 Avenue, Edmonton. Characteristics investigated were arrival rates and queue dispersions. Tabulations were made by verbally counting vehicle arrivals and departures into the speaker of a cassette tape recorder, and later evaluating these counts by timing inter-vehicle arrivals and departures. These statistics clearly showed that:

1. Platoons must be accounted for. The Chi Squared Test showed that the Poisson arrival rate was not applicable for the overall cycle, but that it was applicable for the period between platoons.
2. A constant queue discharge headway and velocity could be used to simulate queue dispersion with very little error.

Consequently the program was written using the constant queue discharge feature and the mixed platoon/random arrival feature. Debugging of the final model was accomplished using the above statistics as typical input data.

In order to validate the model, it was decided that time-lapse photography was the best available approach. By filming the intersection at one second intervals, the arrival rates

and percentage of turners for each lane were easily deduced. Furthermore real travel time through the defined system could also be evaluated for each vehicle.

In order to accurately account for travel time through the system, the entire queue for all lanes must be accounted for. Even filming one artery at a time, this coverage required an excellent vantage point. Since the intersection of 109 Street and 82 Avenue lacked such a vantage point, validation was performed on two other busy intersections - 109 Street and Jasper Avenue and 110 Street and Jasper Avenue. Due to severe technical problems it was possible to analyze only the films of three arteries - each for a period of thirty minutes. All films were taken during the afternoon peak hour.

Actual vehicle timings were deduced from the film by the use of a projector equipped with a digital frame counter. Arrival rates and turn probabilities were then used as input to the simulation program and the simulated mean travel time was then compared with the real mean travel time as measured by the film. The results of this validation process are outlined in Chapter IV.